NUCLEONICS

AEC's Top Management: The Strauss-Nichols Team...page 76

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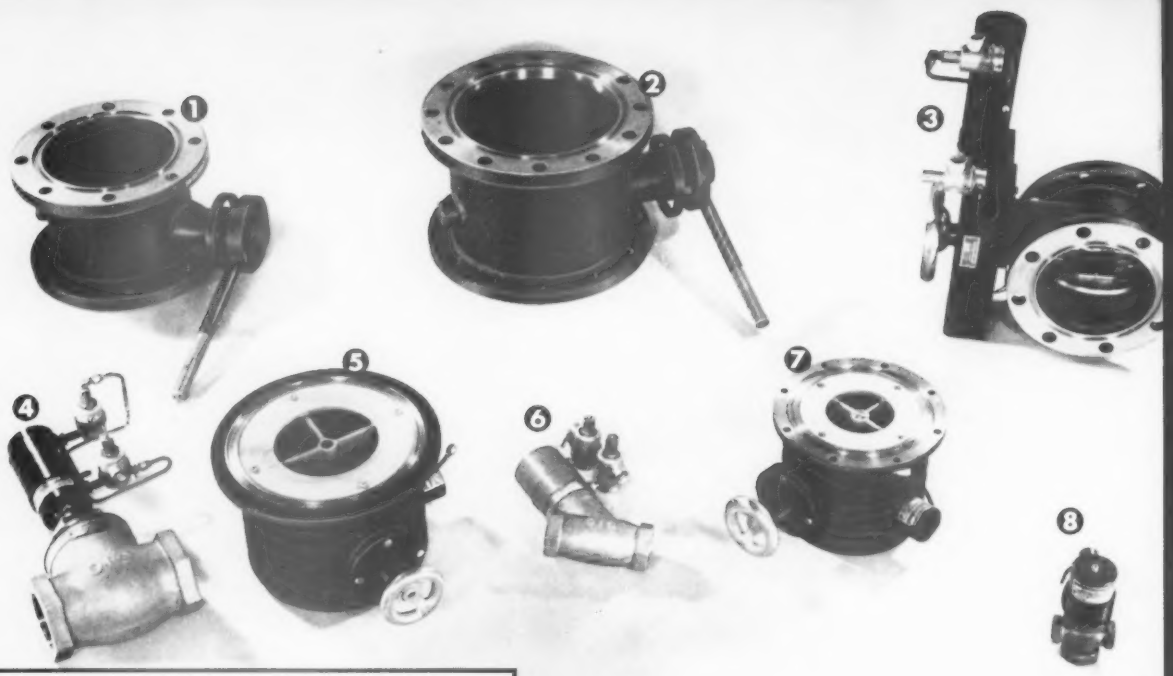

❶ 6-inch QSV series hand operated quarter-swing valve.

❷ 12-inch QSV series hand operated quarter-swing valve. The QSV valves afford the largest practical unblocked aperture plus the shortest over-all length, the important considerations in good vacuum valve design. They are being used to control vacua of the order of 1 x 10^{-9} mm Hg. Available in 4″, 6″, 8″, 10″, and 12″ sizes.

❸ 6-inch pneumatically operated quarter-swing valve. This series ranges in size from 4″ through 16″ nominal diameter.

❹ 3-inch series PV-02 pneumatically operated solenoid controlled globe valve. This makes possible remote control of vacuum pumping systems. Used with CVC thermocouple, Pirani, or ionization gauge controllers it protects an evacuated system from accidental pressure surges.

❺ This 6-inch type VTSB-6 combination valve and baffle serves as a valve capable of isolating a diffusion pump while providing a roughing port, and functions as a water-cooled baffle that can stop backstreaming oil vapor from entering the system.

❻ 1½-inch pneumatically operated solenoid controlled type PV-03 globe valve.

❼ 4-inch VTSB-4 combination valve and baffle.

❽ This ¾-inch NPT type SV-09 normally open solenoid operated valve works on either AC or DC current.

❾ Large right angle pneumatically operated, solenoid controlled, water-cooled high vacuum valve useful with CVC's ejector and diffusion pumps in 14″, 20″ and 32″ sizes.

Which of these *high vacuum valves* match your requirements?

Hand operated—pneumatically driven, solenoid controlled—AC or DC solenoid operated—or a combination valve and water-cooled baffle. . . . Whatever your requirement, *the right CVC* leak-tight, high vacuum valve is available from stock.

Simple to operate, easy to maintain and trouble-free—these high vacuum valves are designed for minimum impedance to the gas flow. In addition, all are guaranteed leak-free and capable of maintaining the lowest commercially feasible vacua.

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formerly DPi Vacuum Equipment Dept.

Consolidated Vacuum Corporation

Rochester 3, N. Y.

designers and manufacturers of high vacuum equipment

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JUNE • 1954

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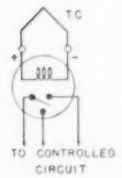

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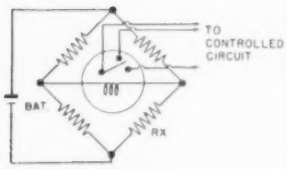
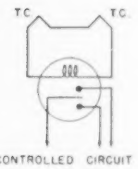
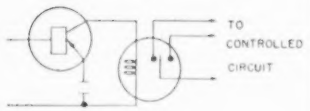


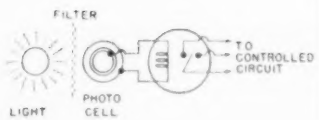
Resistance Selection



Temperature Differential Control



Transitor Selection



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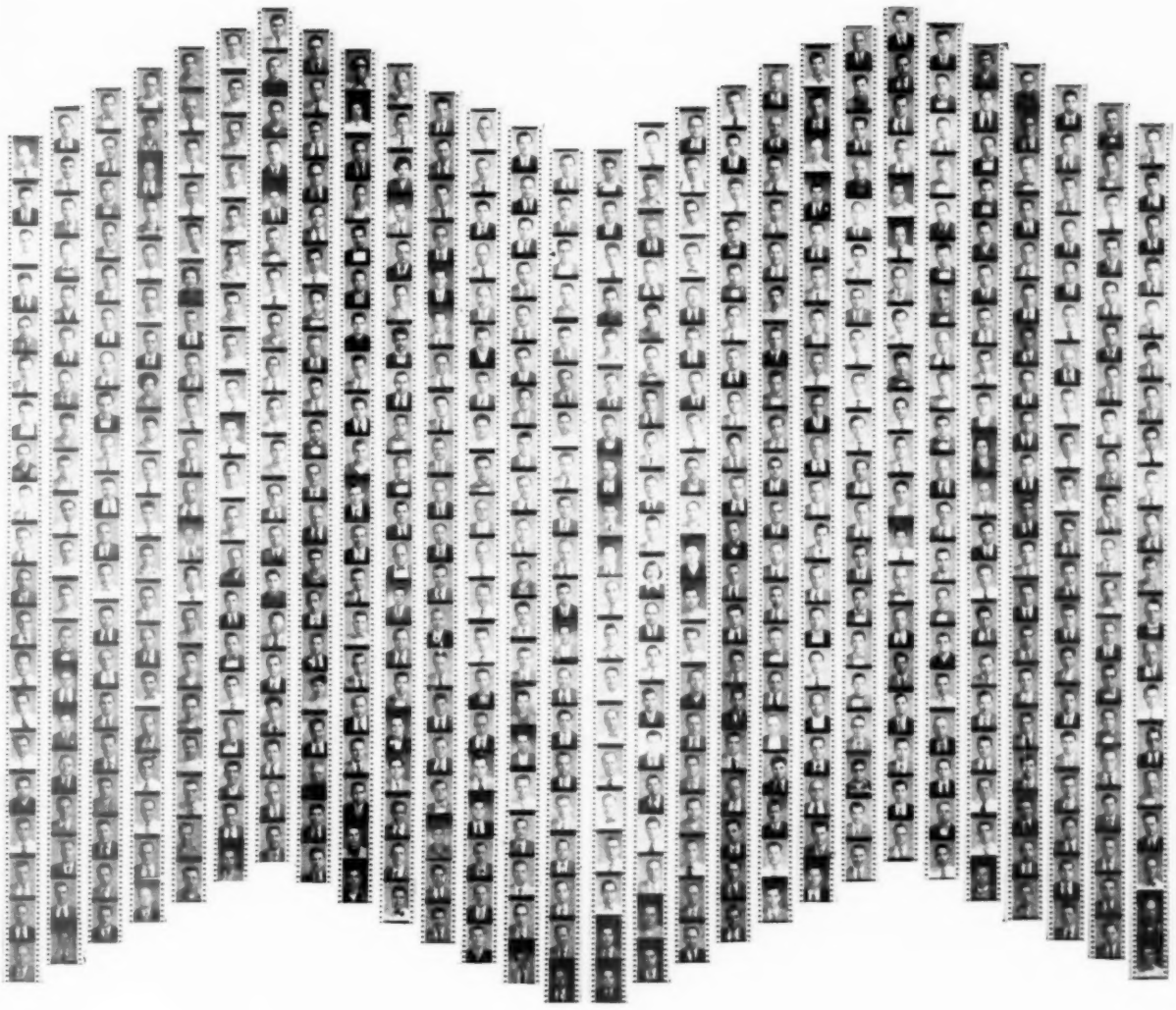

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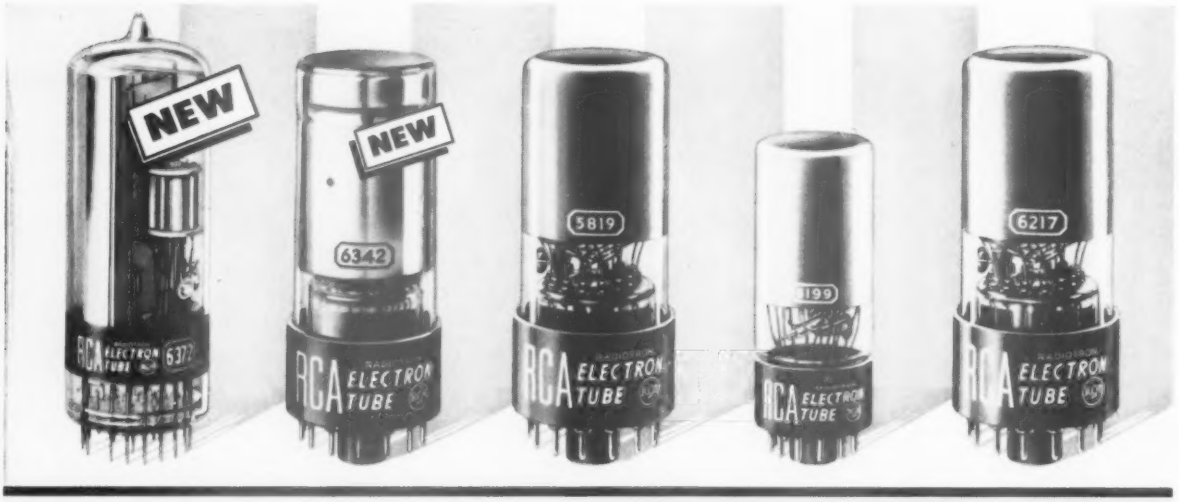

Check your application—pick your multiplier phototube

RCA Type	Application	Spectral Response	Wavelength of Max. Response (Angstroms)	Sensitivity at Max. Response (ua/uw)	Equivalent Noise Input at 25° C—Lumens
6372	Scintillation Counting	S-4	4000	18,600	1×10^{-10}
6342	Scintillation Counting	S-4	4000	7,000	7×10^{-12}
5819	Scintillation Counting	S-4	4000	23,200	2×10^{-11}
6199	Scintillation Counting	S-4	4000	22,300	4×10^{-12}
6217	Spectrometry	S-10	5600	8,500	4×10^{-11}
1P21	Light & Color Measurements	S-4	4000	74,000	5×10^{-13}
1P22	Colorimetry & Spectroscopy	S-8	4200	370	Over 1×10^{-10}
1P28	Light & Color Measurements	S-5	3400	22,600	7×10^{-12} (For ultraviolet, 6×10^{-15} watts)

From the pioneer . . .

the most extensive line of Multiplier Phototubes for special applications

The extraordinarily high amplification obtainable from RCA Multiplier Phototubes makes them particularly applicable to the detection and measurement of low levels of illumination. Coupled with suitable phosphors, many of these tubes are especially useful for detecting and measuring nuclear particle radiation.

The new RCA-6372 utilizes a semicylindrically shaped, semitransparent photocathode with an area of 12⅛ square inches, making it extremely useful in certain scintillation-counting applications such as the detection of alpha particles.

The new RCA-6342, for fast-coincidence scintillation counters, features small spread in electron transit time and relative freedom from after pulses. Its "head-on" design, with flat face, allows excellent optical coupling between the cathode and the phosphor crystal. This tube has a focusing electrode to permit optimizing the magnitude, uniformity, or speed of the response in critical applications.

RCA-5819, with its head-on photocathode of large diameter, may be used in scintillation counters for the detection and measurement of nuclear particle radiation, and in other applications involving low-level, large-area light sources.

RCA-6199, a head-on type, is particularly suitable for portable scintillation counters. It features a flat face and small size. Like the larger 5819, it has maximum response at about 4000 angstroms, has high sensitivity to blue-rich light and negligible sensitivity to red.

RCA-6217, also a head-on type, is especially useful in color densitometers, spectrometers, color comparators, and other applications calling for good red sensitivity.

RCA-1P21 has superior signal-to-noise ratio. It is especially desirable for spectrometers, astronomical telescopes, and scintillation counters using "light piping."

RCA-1P22 has a range of spectral response approximating that of the human eye. It is especially useful for colorimetry, spectroscopy, and other applications involving low light levels.

RCA-1P28 has an envelope of special glass which transmits ultraviolet radiation down to about 2000 angstroms. This feature makes it useful in specialized industrial and scientific applications such as spectrophotometry.

For further information on RCA Multiplier Phototubes contact your nearest RCA Field Office:

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415 S. Fifth St., Harrison, N. J.

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ELECTRON TUBES **HARRISON, N. J.**

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Advances in Applied Radiation

DEVELOPMENTS in the FIELD OF APPLIED RADIATION ENERGY, its APPLICATIONS and the APPARATUS USED TO PRODUCE IT

Radiation Facilities at High Voltage

The versatility of today's accelerators is demonstrated by the radiation power available to industry for experimental and process work at High Voltage's plant in Cambridge:

- Electron energies up to 2.25 MeV capable of delivering dosages of ionizing power up to 50 million gram rep per second — two hundred times greater than the *hourly* output of a kilocurie source of Cobalt. Our Van de Graaff facility can completely sterilize samples at rates up to 200 gross pounds of material per hour, or can deliver massive radiation doses to plastics or chemical systems on a continuous process basis.
- X-ray intensities up to 300 roentgens per minute at 50 cm. Both 1- and 2-million-volt x-rays are available for radiography or research.
- Positive ions (both protons and deuterons) in the range from 0.75 to 2.0 MeV at continuous beam currents up to 50 microamperes.
- Thermal neutron fluxes up to 5 x 10^{5} n/sec-cm^{2}.
- Monoenergetic neutrons from the kilovolt range up to 6 MeV.

Three accelerators in our plant are being used on a contract basis by major industrial companies. We believe these facilities are unmatched in the world today.

The Superiority of Particle Accelerators as Radiation Sources

As a company whose business is the practical application of radiation energy, it is High Voltage's job to investigate alternative sources of this energy — nuclear reactors, pile-produced radioactive sources, and the by-products of nuclear fission — as well as the particle accelerators. *For most applications, including research, the superiority of machine radiation sources is startling.*

Radioactive sources in the multi-megacurie range would have to be available at a cost, including shielding and transportation, of a few cents per curie before the power capabilities and costs of the accelerators *available today* could be matched for commercial use. Even in experimental research, electron sources have become a practical necessity where dynamic systems requiring high dose rates are involved. The very low output and absorption of gamma radiation from radioactive isotopes makes it impossible to produce useful yields in a reasonable period of time.

Long recognized as precision sources of a wide range of monoenergetic neutrons for research, today's Van de Graaff particle accelerators are also capable of producing, with virtually no gamma background, neutron fluxes which match those available at the experimental portals of large nuclear piles. Neutron fluxes of 10^{10} n/sec-cm^{2} over a sphere of 10 cm in diameter appear feasible with today's accelerator technology, with equipment costs which are a fraction of those associated with the construction of a nuclear reactor.

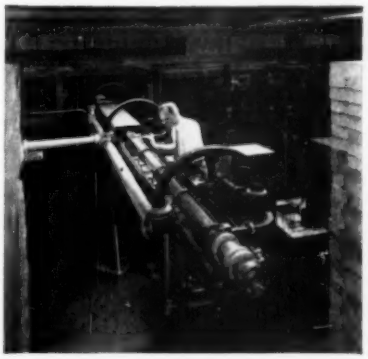
New Tool for the Oil Industry

High Voltage's Model HN 0.5-million-volt Van de Graaff is now being used by Well Surveys, Inc., Tulsa, Oklahoma, in studying the scattering characteristics of radiation in soil strata.

Well logging has become increasingly important in oil-well exploration, and today nearly all rotary-drilled wells are logged at least once before completion. Of all available techniques of logging, radioactivity logging, developed by Well Surveys, Inc., has proved to be the only method of locating and identifying subsurface formations in both open and cased holes. In the past, research in scattering characteristics has been carried out with radioactive isotopes, but these have lacked both the necessary intensity and the desired energy. Well Surveys' new Van de Graaff can produce a flux of neutrons as great as that from several hundred grams of radium-beryllium. With this compact accelerator, Well Surveys expects to gain more precise data for increasing the efficiency of oil-well completion and exploitation.

New Linear Accelerator

High Voltage has delivered the first microwave linear accelerator to be built commercially in the United States. Combining radar and accelerator techniques, this unit is controllable in energy from 10 to 50 million volts, and will be used to study the effectiveness of direct high-energy electron bombardment in cancer treatment. Completely engineered by High Voltage, it is based on designs of the Microwave Laboratory, Stanford University, and employs klystron amplifier tubes and wave guides developed and constructed at Stanford.



Radar pulses from the klystrons carry bursts of electrons along the 16-foot wave guide in which a very high vacuum is maintained. At the end of the guide, the electrons have attained a speed nearly equal to that of light and weigh 100 times more than when they started. A thin aluminum window maintains vacuum in the wave guide and allows the electron beam to be used externally in cancer-treatment research.

With the successful completion of this apparatus — the first linear accelerator for medical use in this country — High Voltage has added both a new product and a new technology to its versatile line of accelerators for medicine, research, and industry.

This is an electron-
a negative personality but usually very fast.

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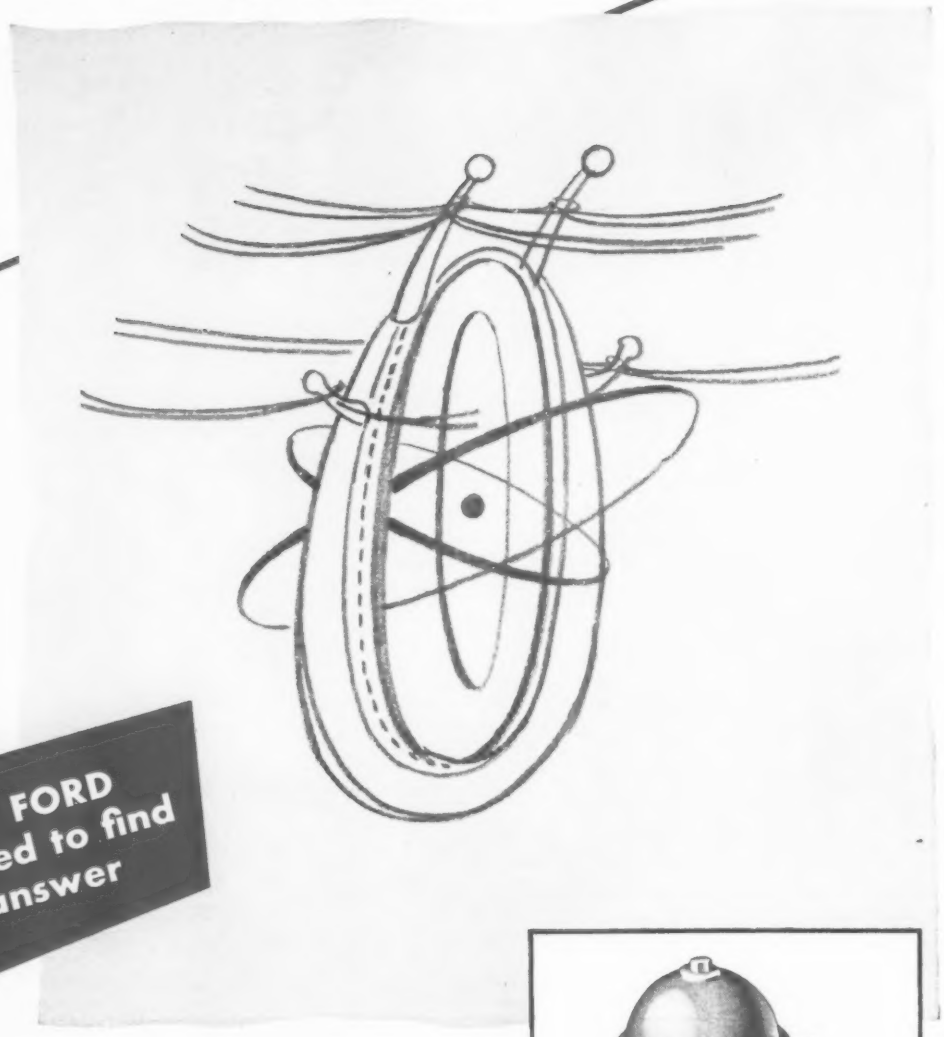
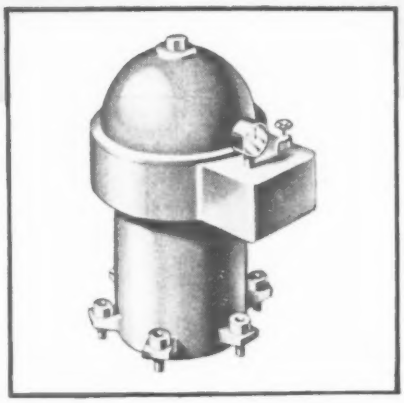
HOW TO MAKE A HARNESS
for an Atom



...and FORD was asked to find the answer



Taming the monster power of a nuclear reactor requires precision control of all the elements. Ford Instrument is designing controls that seek and hold the optimum power level of the pile . . . and keep the rods so exactly set that the reactor's energy is harnessed . . . safely, securely.

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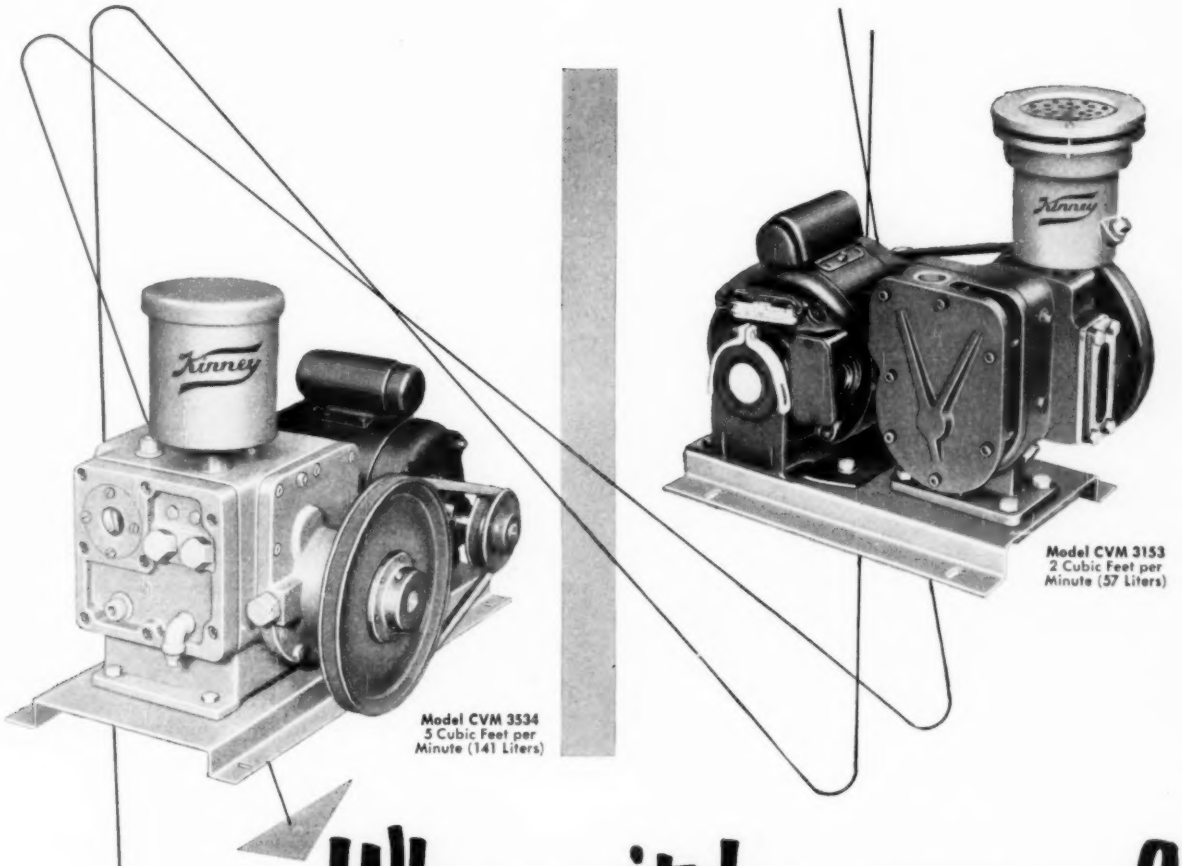

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Minute (141 Liters)

Model CVM 3153
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Minute (57 Liters)

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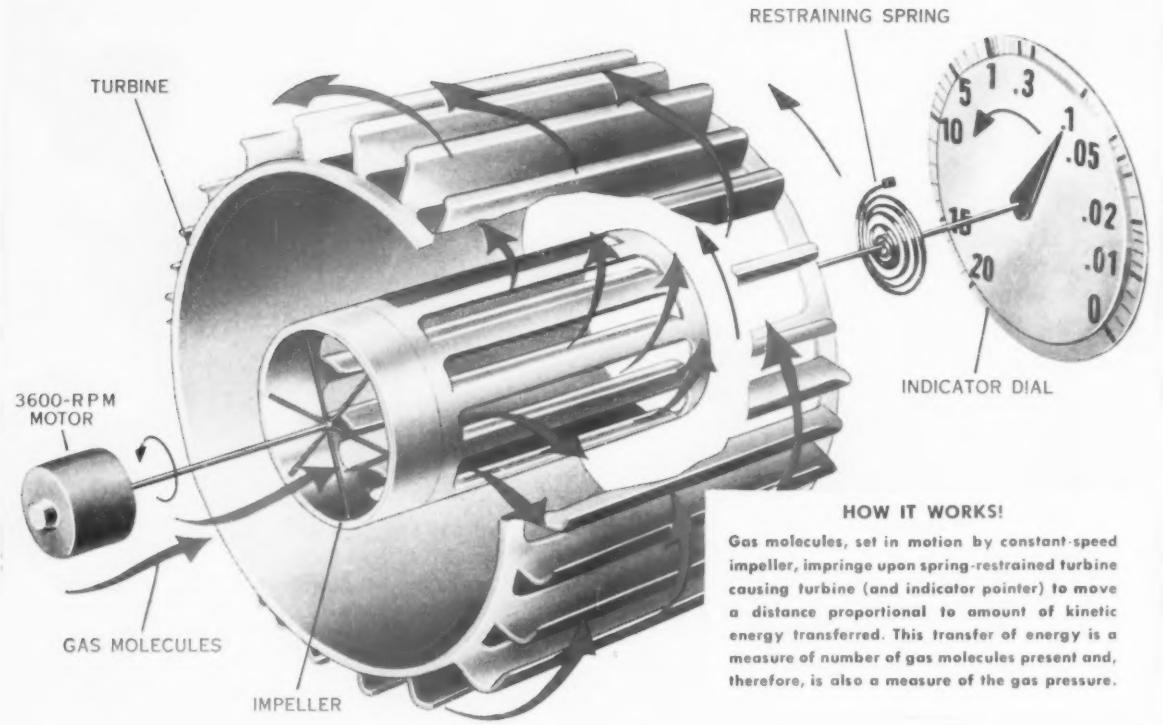


HOW IT WORKS!

Gas molecules, set in motion by constant-speed impeller, impringe upon spring-restrained turbine causing turbine (and indicator pointer) to move a distance proportional to amount of kinetic energy transferred. This transfer of energy is a measure of number of gas molecules present and, therefore, is also a measure of the gas pressure.

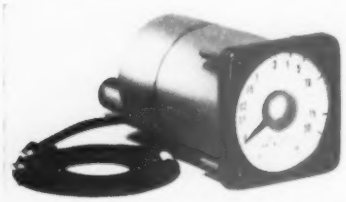
FOR SIMPLIFIED VACUUM MEASUREMENT—EASY OPERATION—EASY INSTALLATION . . .

G.E. Announces Revolutionary New Molecular Vacuum Gage

Similar to a "fluid clutch" in principle of operation, this new entirely mechanical molecular vacuum gage overcomes many of the problems encountered in the use of other type vacuum gages.

NO PRIMARY ELEMENT TO BURN OUT

Having no electronic tubes or other electrical detecting devices, the new G-E molecular vacuum gage assures continuous operation without time-consuming delays caused by electrical failure such as tube burnout.



New G-E gage is easy to mount, and its small size requires but a minimum of panel space.

UNHARMED BY ATMOSPHERIC PRESSURE

Because this new device may be opened to atmospheric pressure suddenly without damage to the instrument, it is especially valuable where personnel may be untrained in the use of complicated instruments.

SIMPLIFIED OPERATION

The new G-E molecular vacuum gage requires no complicated setting of control knobs. Direct-reading, the instrument calibration remains unaltered through continuous operation. The long-scale span in the high-vacuum range, and the easy-to-read indicator dial assure accurate readings.

HIGHLY VERSATILE

Available in two types, the molecular vacuum gage is supplied with a scale for the direct reading of dry air, or with a linear scale which may be calibrated for other gases. It is therefore suitable for laboratory and research installations. Price is $193.00.* For further information, contact your nearest G-E Apparatus representative, or write for Bulletin GEC-986 to: Section 605-78, General Electric Co., Schenectady 5, N. Y.

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LATE NEWS

Compiled by NUCLEONICS June 2
. . . for publication June 7

Package Reactor Bids AEC will issue bid invitations around July 15 to qualified contractors for design and fabrication of the first package power reactor for military use. At least seven firms have indicated their interest in bidding on a fixed-price basis on the 1,250-kw plant which will cost around $2-million. One firm has said it would fabricate the fuel elements with a guarantee of a five-year life.

•

Industrial Assistance AEC's Office of Industrial Development, set up in 1952, has been abolished. Some of its functions are to be carried out by the staff of A. Tammaro, new AEC assistant general manager for research and industrial development.

•

Competitive Homogeneous Power AEC believes that a homogeneous power reactor built in the 1960's may produce competitive 5.9 mills/kwh power. The cost of such a plant would break down as follows in mills/kwh (dollars per kw given in parentheses): operation and maintenance, 0.5; fuel (uranium, processing, fabrication), 1.0; fixed charges, 2.0 ($100); steam generation system, 0.4 ($20); turbogenerator system, 2.0 ($100).

Reactor system costs of $100/kw would break down as follows (in $/kw): reactor tank, $3; gas control system, $4; solution storage and handling system, $4; circulation system and pumps, $6; building and shield, $8; miscel., $15; inventory of D_2O, U and Th, $60.

•

International Meeting Great mystery surrounds proposed international meeting on peacetime atomic energy recently announced by AEC Chairman Strauss. There is no known sponsor of the affair. National Science Foundation and National Academy of Sciences have been reported as cosponsors but they disclaim this. It is also reported that the meeting will be held outside of this country.

•

Impact of Atomic Energy Westinghouse Electric Corporation has a significant stake in the future of atomic energy. Gwilym A. Price, president of Westinghouse, said on May 26 that the long-range business optimism of his company is based to a considerable extent on atomic energy developments. He also predicted that by 1963 one million kw of electricity would be produced by nuclear power plants.

•

Thermonuclear Power Senator Hickenlooper of Joint Committee on Atomic Energy in a May speech pointed up thinking on possibilities of peacetime applications of controlled thermonuclear reactions. There is optimism in other quarters that industrial power plants using fusion will be feasible. It is reported that AEC is carrying out, on a priority basis, very hush-hush, highly compartmentalized work at several sites. Although a peacetime effort, existence of program is reportedly being kept quiet for administrative reasons.

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Market for Radiation Sources Consensus of industry is that more than 50 teletherapy radiation sources will be sold in the next few years. AEC expects that by end of '54 it will have 34,000 curies of high-specific-activity cobalt-60 available. Nine cans of cobalt went into the Material Testing Reactor early last year. They will have specific activity of 50 curies per gram. Thirty more cans were placed in the low-flux zone of MTR in November, 1953. The newly repaired Canadian NRX reactor will be producing 30 curie per gram cobalt by the end of '55 or early '56.

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Reactor Bets In a bold statement at the May 24 conference of the Atomic Industrial Forum, the General Electric Company predicted that nuclear power would be competi-

tive in this country in the period 1959 to 1964. GE also wagered that two reactor types are most likely to succeed: (1) the light-water-moderated and cooled boiling water reactor and (2) the graphite-moderated water-cooled reactor. To support its work on the first type, GE hired Sam Untermyer of Argonne National Laboratory. Untermyer, who reported at Schenectady June 1, played a key role in Argonne's work on the boiling water reactor experiment.

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Revision of Law Second version of Cole-Hickenlooper bill to amend Atomic Energy Act came out May 25. It goes a long way to satisfy critics, to tighten up wording and to delineate powers granted AEC. Considerable clarification is achieved by stating provisions in positive way rather than including things under exceptions. Here are key changes made in second version (see p. 77 for earlier comments):

AEC can only conduct research for others when AEC finds private facilities "inadequate to the purpose."

It is mandatory, rather than permissive, that AEC shall buy the fissionable material produced by any licensee at a "fair price" determined in part by AEC's need for the material.

Each year, the President shall determine quantity of fissionable material available for distribution. If demand for fuel exceeds amount available, AEC shall favor those AEC feels will do country most good. AEC may withhold licenses if it feels it must conserve fissionable material.

Requirement of report to Congress by AEC prior to granting of first license for a practical nuclear power plant is eliminated. In place of report, other safeguards have been inserted; e.g., Joint Committee will hold hearings each year to check working of the law.

To facilitate financing of nuclear plants, licensee may mortgage his plant which would be transferable to lender in event of foreclosure.

License period is changed from 25 to 40 years.

Entire chapter on control of information is changed to authorize AEC to declassify information so as to "enlarge the fund of technical information" and to foster "industrial progress and public understanding." Three-year life of restricted data is eliminated; instead AEC is instructed to maintain a continuous review of restricted data for declassification purposes . . . $2,500 fine for communicating restricted data would now only be imposed if the individual knew or had reason to believe that he was communicating restricted data and only if he knew or had reason to believe that the recipient of data was not authorized to receive it. Innocent or inadvertent disclosure is not subject to penalty.

Board for reviewing licensing decisions has been dropped. Courts must be resorted to. Exclusion of cases involving restricted data has been dropped.

AEC can grant one license covering activities that under original bill required several.

Normal patenting still permitted. However, patentee must not have conceived idea while under contract with AEC, even if he spent own money.

Positive authorization is given to AEC to distribute fuel to foreign nations, and to companies to export utilization or production facilities.

Licensees are responsible for damages resulting from use of fissionable material.

AEC is specifically authorized to issue licenses for pilot or prototype reactors.

Requirement of no alien directors and limitation of 5% on alien stockholders in licensee companies have been dropped.

Foreign nations may have title to fissionable material received from U. S.

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AEC Views on Law In first public statement on pending Cole-Hickenlooper bill, AEC offered substantial support to bill on June 2nd. Only major objection was to patent section. Recommendation was made that AEC be permitted, for five years, to declare a patent as affecting the public interest. In testimony, AEC presented informal "7-b" report on implications of atomic developments.

NUCLEONICS JUNE, 1954

Jerome D. Luntz, *Editor*

A New Era of Cooperation

As is pointed out elsewhere in this issue, there is a good chance that a major revision of the Atomic Energy Act will be approved by Congress this year. One of the main purposes of the amendments will be to make possible the establishment of a nongovernment atomic energy industry. This will not mean, however, that there will be a sudden schism between government and industry. On the contrary, we shall be entering a new era of cooperation.

To date, the multibillion dollar atomic energy program has been carried out by industry as contractor to the government. The results and the relationships have been quite satisfactory. There is no reason to believe that this method of running the program will be changed in the near future.

What then will the new cooperation be? Interim revision of the law is proposed to enable industry to start activities in the broad field of reactor technology. Because the common defense and security and the health and safety of this nation are involved in the building of a number of nuclear power plants, the Congress feels that the government, via the Atomic Energy Commission, should have considerable control and regulatory power.

As presently written, the powers granted AEC are very broad so that the Commission would have life or death control over the industry. On the assumption that these basic powers are not radically changed in the final bill acted upon by Congress (as they are not likely to be), it shall fall to the lot of AEC to interpret its powers so as to best implement the intent of Congress.

For example, we take for granted that Congress wants a vigorous industry started. To facilitate this, it will be necessary for AEC to have a positive, progressive outlook in the exercise of its responsibilities. Its attitude should not be one of acting in the capacity of a stern parent trying to keep his children in line. Rather the philosophy should be one of offering every assistance possible to industry to encourage as many companies as feasible to participate.

Some of the areas where difficult AEC decisions will be involved and where the ultimate in intelligence and foresight will be necessary are determinations of: (1) the quantity of fissionable material to be allocated to industry each year; (2) prices that the government will charge and pay for original and regenerated fuel, respectively; (3) the qualifications of applicants for licenses to build and operate reactors; (4) size of reactor exclusion areas and other health and safety matters; (5) qualifications of foreign customers for American reactors; and (6) access to technical data for private companies.

In the past on at least several occasions AEC has been squeamish about going as far as Congress said the law would permit AEC to go. For example, AEC was very conservative for quite some time on the granting of certain patent rights to companies spending their own money under contract with AEC. Also, AEC was frequently reluctant to declassify data on the grounds that its disclosure would not adversely affect the common defense and security.

In addition to the need for good faith on the part of AEC, industry must also act wisely, particularly once fissionable fuel gets into widespread use. Uranium and plutonium should be used as efficiently as possible. The health and safety of employees and the community must be given the utmost consideration. AEC should be given full access by industry to private nuclear power plant data it requires under the law for the protection of the nation.

If both the Atomic Energy Commission and private industry fully accept their responsibilities under the proposed legislation, there is no reason that we should not have a vigorous industry that will enhance our national security and the standard of living of the world.

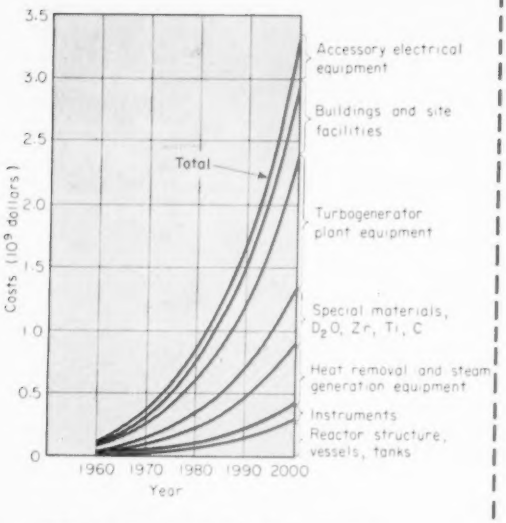

FIG. 1. Projected annual investment costs of nuclear electric plant equipment

By JAMES A. LANE
*Oak Ridge National Laboratory**
Oak Ridge, Tennessee

Growth Potential

THE ATOMIC ENERGY COMMISSION announced in March its five-year program for development of nuclear power systems (*1*). This program encompasses several promising routes for the achievement of economically competitive nuclear power.

To provide assistance in analyzing the content of this program, this paper presents factors involved in choosing the best system and estimates power costs and probable sizes of the industries that will result.

THE OPTIMUM SYSTEM

At the present time, there is no clear indication which type of reactor will ultimately produce the most economical power. Fundamentally, the choice of the optimum system revolves around three main problems: the selection of the coolant, the arrangement or type of fuel, and the neutron energy. Stated differently, the dilemma boils down to a question of sodium vs. water, heterogeneous vs. homogeneous, and fast vs. thermal. The fact that these variables may be combined to yield many feasible types of reactors, each with firm adherents, may be an indication that there is no "best" reactor. The following comparison of the pros and cons clearly indicates the difficult task that faces those charged with selecting a system for the most economic nuclear power plants.

Sodium vs. Water

The controversy over choice of coolant stems mostly from the fact that there is no ideal coolant. Since power cost is very sensitive to the efficiency with which heat is removed from the reactor core, all coolants have to be pushed to their maximum capabilities to achieve an economic nuclear plant. A comparison of the characteristics of nuclear plants using sodium and water is shown in Table 1.

These data show that sodium offers higher thermal efficiencies and relatively lower pressure operation than obtainable with water. Partially offsetting this is the cost of the complicated handling equipment due to the high melting point of sodium and its chemical activity.

Both sodium- and water-cooled nuclear power plants produce steam at lower pressures than is commonly used in modern conventional plants. Thus investment cost of a nuclear plant's turbogenerator portion is higher than the investment cost of the corresponding portion of a conventional plant operating at about 1,000° F and 1,500 psia. This is shown in Table 2, along with the power costs associated with this portion of the plant. The difference in power costs due to lower steam pressures in water-cooled plants compared to sodium-cooled plants amounts to about $20/kw of capability or about 0.4 mills/kwh.

Hetero- vs. Homogeneous

Homogeneous reactors, strictly speaking, are distinguished from heterogeneous reactors only by the degree to which fuel is dispersed through the moderator. When the dispersion reaches the point where the thermal neutron flux in the fuel is the same as in the moderator, the reactor is said to be homogeneous. Possible homogeneous types include solid-fuel:solid-moderator (impregnated graphite); solid-fuel:liquid-moderator (MTR type); mobile-fuel:liquid-moderator (pebble pile); and solution or slurry systems. Because aqueous-solution or slurry reactors represent the most practical and best known of the homogeneous systems, the term "homogeneous reactor" commonly refers to this type. Most of the advantages or disadvantages commonly attributed to homogeneous reactors are derived from considerations of aqueous-solution or slurry reactors. Nonaqueous (that is, liquid-metal or fused-salt) reactors have received some attention and may have special merit for some applications.

Three advantages of homogeneous reactors stand out. First, since heat is generated within the fuel solution itself, there is no heat transfer problem

* Operated by Carbide and Carbon Chemicals Co. for the U. S. Atomic Energy Commission.

Coolant selection, arrangement and type of fuel, and neutron energy are considered as factors in determining the best power-reactor system. Power costs and probable sizes of the resulting raw material, generating, and equipment industries are estimated

# of U. S. Nuclear Power Industry

inside the reactor core to limit rate of heat removal, and second, the fluid nature of the fuel permits purifying and adding fuel without going through the complicated cycle of unloading, cooling, dissolving, chemical processing and refabrication of fuel elements. Finally, it is possible to design aqueous-fuel reactors that are self-stabilizing against changes in reactivity. This eliminates the need to rely on the mechanically-driven control rods actuated by electronic circuits that are usually necessary with heterogeneous reactors.

Offsetting these advantages are the corrosive nature of aqueous fuel solutions and the problems introduced by circulating highly-radioactive solutions through external heat exchangers and other equipment. In addition, aqueous homogeneous reactors are limited to the use of D_2O, since the high uranium concentrations necessary in H_2O-moderated systems cannot easily be obtained with uranium in solution.

With respect to the problem of heat removal, the design of fuel elements for heterogeneous reactors is moving toward more complete dispersions of fuel and coolant (though not necessarily fuel and moderator) with elements taking the form of bundles of rods, parallel plates or internally-cooled concentric cylinders. The specific power per unit weight of fuel in such designs approaches that obtainable in solution reactors. The utility of such schemes

TABLE 1—Characteristics of Sodium- and Water-Cooled Nuclear Plants

Characteristic	*Coolant*	
	Sodium	*Water*
Pressure, psia	50–80	1,000
Inlet temperature, °F	600	400
Outlet temperature, °F	900	500
Melting point, °F	208	32
Steam conditions, °F, psia	750, 485	370, 175
Thermal efficiency, %	30	24
Shielding req'd. for pipe lines, ft of barytes concrete	6–7	1
Flow rate/kw elect. capacity, lb/hr	100	200
Radiation effect on coolant	None	Decomposes to $H_2 + O_2$
Chemical effect	Reacts violently with H_2O or moist air, slightly with graphite	None
Cost of non-nuclear part of plant, $/kw	110	130

TABLE 2—Investment for Turbogenerator Plants of Varying Steam Conditions

Condition	*Steam*				
	Saturated		*Superheated*		
Steam temperature, °F	388	478	600	800	1,000
Steam pressure, psia	215	560	300	660	1,465
Gross thermal eff.,* %	26.4	30.7	30.5	36.7	41.8
Net thermal eff.,* %	24.7	28.9	28.7	34.8	39.6
Capability, $/kw	125	115	108	100	97
Cost, mills/kwh, at 80% load, 15% charges	2.7	2.46	2.32	2.15	2.08

* Does not include power for reactor plant.

depends on development of cheap methods of fabricating fuel elements with adequate heat-transfer surface.

Due to the high heat transfer coefficients obtainable, the use of boiling water as a method of heat removal offers the possibility of materially increasing the specific power of heterogeneous reactors (*2, 3*). The corresponding advantages for homogeneous-solution reactors are not as apparent since high specific powers can be obtained by circulation without boiling, and the nuclear characteristics of such a system are strongly affected by large amounts of steam in the reactor core. In the case of heterogeneous systems, moreover, it may be possible to use the D_2O or H_2O steam directly in the turbine, whereas the steam from the fuel solution would be highly contaminated with entrained fission products.

Fast vs. Thermal

The technology of full-scale fast reactors has not yet reached the point where nuclear-power economics can be realistically appraised.

Fundamentally, fast reactors are of interest because of the low parasitic-capture-to-fission ratio with high-energy neutrons. With an appropriately high neutron-spectrum, the number of excess neutrons available is great enough that breeding or complete conversion of U^{238} to plutonium is theoretically possible.

In thermal reactors, the high parasitic-capture-to-fission ratio in plutonium reduces the number of excess neutrons available. A thermal reactor fueled with plutonium and U^{238} alone might not breed or even be self-sustaining. Allowing for losses due to chemical reprocessing for each fuel cycle, the practical maximum burnup of U^{238} in thermal reactors is estimated to be about 10%, compared to about 50% for fast reactors.

To sustain the chain reaction with high-energy neutrons, the ratio of fissionable material to fertile material must be relatively high compared to that required for fission with thermal neutrons. This high concentration is disadvantageous in that it decreases the specific power per unit weight of fissionable material and increases the amount of natural uranium required to supply the plutonium for reactor fuel inventories. The situation is especially serious in a circulating-fuel fast reactor where there is a large holdup

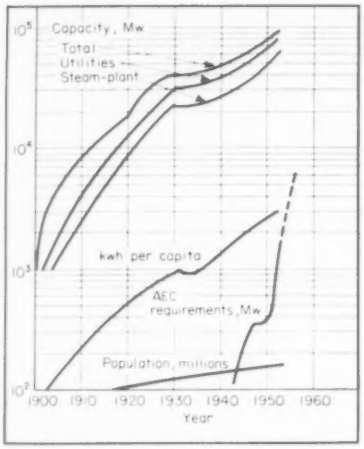

FIG. 2. Growth of U. S. electrical power industry, 1900–1952

outside the core. Thus, this type of reactor appears to be impractical. For this reason, fast reactor systems are restricted to solid or non-circulating types with correspondingly high fabrication and reprocessing costs.

In the case of thermal breeder reactors operating on the thorium-U^{233} system, the optimum concentration of U^{233} (from the standpoint of processing costs and neutron economy) is usually of the order of 3 to 10 kg per ton of thorium. The fuel must be supplied either from bred U^{233} or from the conversion of enriched U^{235} to U^{233}. In either case, the fixed charges associated with this fuel inventory are a significant fraction of the cost of electricity. This is shown in Table 3, which summarizes the fuel and moderator requirements for fast breeders and aqueous thermal breeders, calculated on the basis of the maximum power densities achievable.

In the case of the circulating-fuel thermal breeder, the material in the external heat-removal system is included. To calculate the corresponding fixed charges due to reactor inventories, published costs (*4*) for enriched U^{235} and natural uranium given as $20 gm and $35 lb, respectively, can be used, assuming that U^{233} and plutonium have the same value as U^{235}, and thorium the same value as U^{238}. On this basis, the value of the fuel and fertile material per Mw of installed electrical capacity amounts to about $31,000 for the aqueous thorium breeder and $74,000 for the fast breeder. In the former case, the cost of D_2O at $100/liter adds another $24,000/Mw. Taking a 12% carrying charge for these material inventories and 80% load factor, the corresponding fixed charges due to inventories are 0.9 mills/kwh for the thermal breeder and 1.3 mills/kwh for the fast breeder. If processing costs are added to these charges, it will be difficult to achieve fuel costs less than 1.5 mill/kwh.

It is evident that inventory costs constitute a significant fraction of the cost of power from breeder reactors. Furthermore, the inventory requirements for solid-fuel thorium-breeder reactors may be higher than for homogeneous breeders by a factor of three because of lower specific powers or power densities obtainable.

In the case of the solid fuel nonbreeding or so-called regenerative reactors, there is no enriched-fuel inventory requirement because such reactors use natural or slightly-enriched uranium as fuel and fertile material. It is estimated that the minimum requirement will be about 200 kg of natural uranium per Mw installed electrical capacity for these reactors. It may be that the higher inventory requirements of breeder reactors will tend to offset the higher burnup in nonbreeder reactors.

The problem of heat removal is analogous for both fast and thermal systems. In either case, the nuclear fuel, such as U^{235}, Pu^{239}, or U^{233}, must be diluted to provide adequate heat transfer surface by adding fertile material and some other element of appropriate neutron characteristics. For fast reactors, this diluent is limited to iron, chromium, or other nonmoderating materials. The choice of coolant in fast reactors is limited to a few select materials such as Na, NaK, Hg, or some fused salts. In thermal systems, the choice of diluents, or moderators, and coolants covers a wider range of materials that might, or might not, offer an economic advantage.

To summarize, fast systems enjoy a higher neutron availability, but offer a more limited choice of materials for removing the heat from the reactor core. The higher concentration of uranium necessary for criticality in fast reactors increases the costs due to fuel investment and restricts practical designs to noncirculating-fuel types. The economics of power production are unfavorable in fast-reactor designs involving fuel elements that are costly to fabricate and reprocess. Potentially, however, the value of the additional

plutonium produced from the excess neutrons in fast reactors might be enough to make this type of reactor the most economical power producer.

NUCLEAR POWER COSTS

Charges for the power developed will be based on amortization of plant costs (investment) and on fuel costs (operating expense).

Plant costs. Depending on the particular system and the degree of optimism with regard to possible advances in reactor technology, published estimates of nuclear-boiler plant costs exclusive of the turbogenerator plant vary from $50 to $200 per kw of electrical capability. The cost of the turbogenerator portion of the nuclear plant, moreover, will be slightly higher than that for a conventional plant because a nuclear boiler produces lower pressure steam than a coal-fired boiler. The costs of this portion of the plant have been shown in Table 4 to vary from $97 to $125 per kw capability, depending on the steam pressures. Corresponding fixed charges of the entire nuclear power plant based on 15% of investment costs and 80% load factor will vary from 3.2 mills/kwh to 7.1 mills/kwh. Most nuclear engineers are confident that in the second generation of nuclear plants, at least, total fixed charges in the neighborhood of 4 mills/kwh can be achieved.

Fuel costs. Fuel costs in a nuclear power plant are the sum of the fixed charges due to fuel inventories, the fabrication and reprocessing costs, and the costs due to fuel burned. In breeder reactors particularly, burnup costs are negligible and fuel costs arise only from inventories and reprocessing.

It is often convenient in D_2O-moderated reactors to consider the fixed charges due to D_2O holdup as well as D_2O losses as part of fuel costs. On this basis, the fuel costs are far from negligible even in reactors that make most efficient use of raw materials.

A comparison of the cost of power from a nuclear plant (assuming reasonable advances in reactor technology expected within 10–15 years) with that from a modern coal-fired steam plant is shown in Table 4.

NUCLEAR INDUSTRY SIZE

If competition between nuclear and conventional plants turns out to be as favorable as Table 4 indicates, it is important to determine how fast the nuclear power industry might expand and what the uranium and thorium requirements might be for the various nuclear systems being considered. Such crystal-ball gazing, if not taken too literally, gives some indication of the outlook for nuclear power relative to our nuclear-fuel resources.

TABLE 3—Inventory Requirements of Thermal- and Fast-Breeder Reactors*

Type and material	*Core*	*Blanket*	*Total*
Thermal breeders			
U^{233}, kg	0.3	0.5	0.8
Thorium, kg	—	190	190
D_2O, liter	115	125	240
Fast breeders			
Plutonium, kg	2.0	0.9	2.9
U^{238}, kg	10	200	210

* Basis: 1 Mw installed electrical capacity; maximum achievable power densities in core and blanket.

TABLE 4—Cost of Power from Nuclear and Coal-Fired Plants*

Item	*Cost*	
	Conventional	*Nuclear*
Investment, $/kw		
Reactor or boiler	50	100
Turbogenerator	100	120
	150	220
Power, mills/kwh		
Fixed charges	3.2	4.7
Fuel	2.8	1.0
Operation & maint.	1.0	1.0
	7.0	6.7

* Basis: average large-scale plants; no research and development costs included; coal, $7/ton; natural uranium, $35/lb; fixed charges, 15%; load factor, 80%.

The starting point for such an estimation is the growth of the U. S. power industry as shown in Fig. 2. The inflection in the curves due to the depression in the thirties makes extrapolation to our future capacity difficult. If the present slopes are projected, the installed generating capacity will increase about thirtyfold in the next 50 years. More conservative estimates predict an eightfold to fifteenfold increase by the year 2000.

The estimated growth of the power industry (*5*) (which came from the same study) is based on a 4.3% increase per year (*6*). Taking the slope of the total-capacity curve gives the annual increase in plant capacity. This increase varies from 5,500 Mw/yr in 1960 to 30,000 Mw/yr in A.D. 2000.

Just what fraction of these new plants will be nuclear plants is considerably more difficult to predict since this depends on unknown economic factors. As a starting point, however, we can look at the present day progress toward industrial nuclear power and estimate the possibilities for the immediate future. Indications are that one or two nuclear plants with a total capacity up to 500 Mw may be built by 1960. This would comprise about 10% of the new plants added in 1960. At the other end of the scale, that is in A.D. 2000, possibly 50% or more of the new plants added might be nuclear plants. On this basis, the nuclear plant fraction of new plants will increase 1% per year, resulting in the curve shown in Fig. 3. Integrating this curve results in the predicted installed nuclear plant capacity as shown. This capacity increases from 500 Mw in 1960 to 210,000 Mw in 2000. A few years delay in the construction of the first nuclear plants would tend merely to displace this curve by that number of years.

Nuclear Fuel Needs

It has often been stated that we must develop breeder reactors in which more nuclear fuel is produced than burned, since this makes expansion of a nuclear power industry possible independent of raw material supplies. Such statements overlook the fact that all reactors require a certain amount of fuel or fertile material in the core or blanket or in the chemical process plants that never gets burned. The amounts of these reactor and process plant inventories depend on the efficiency of the heat-removal system, the desired neutron economy, and the chemical process cycle.

It turns out that some nuclear systems are appreciably better than others with respect to these inventories. Fast breeders, for example, require high concentrations of fissionable material for criticality and good neutron economy. In thermal breeders, on the other hand, the most economic system is not always that which has the minimum fuel inventory. For example, minimizing the amount of fuel (and

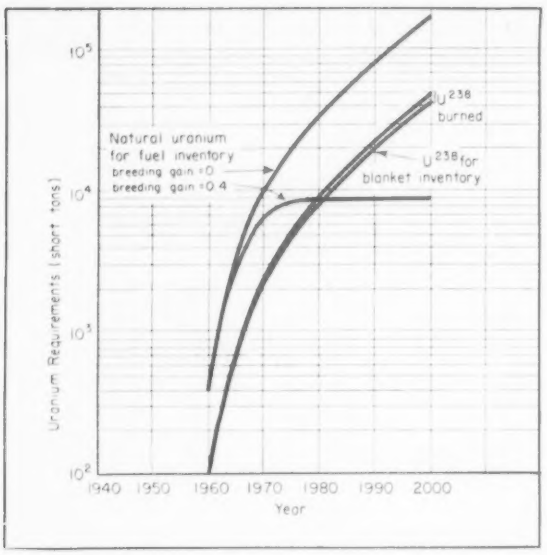

FIG. 3. Cumulative material requirements for fast breeder systems

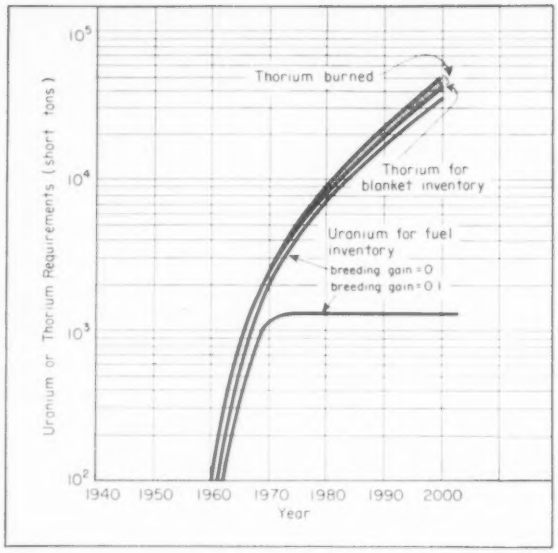

FIG. 4. Cumulative material requirements for thermal breeders

heat produced) in the blanket of an aqueous homogeneous breeder maximizes the costs charged against the D_2O in the blanket. Since some nonbreeding systems have a high burnup but low reactor inventory, it is not evident *per se* which of the various reactor types requires the minimum *total* amount of material.

Calculations of possible heat removal rates in solid-fuel and circulating-fuel reactors can be used as a basis for estimating minimum nuclear fuel requirements, keeping in mind that such systems may not be the most economical. The material requirements for thermal and fast breeders calculated on this basis are shown in Table 3. The corresponding inventory requirement of converter reactors fueled with natural or slightly-enriched uranium will amount to 180 kg per Mw installed capacity, which is approximately the same as the fertile material requirement in the breeders.

Using the projected expansion of the nuclear power industry given in Fig. 2 as a basis, the cumulative material requirements for a fast-breeder system are shown in Fig. 3. The plutonium fuel requirements are expressed in terms of equivalent natural uranium, assuming a conversion of 3.5 kg per short ton. In reactors that have a breeding gain above zero, the bred plutonium will ultimately be produced at a rate greater than the expanding power industry and no further raw material will be required. This is shown in Fig. 3 for fast breeders with an arbitrarily assumed breeding gain of 0.4. At this breeding gain, the fuel doubling-time is 6.7 years and the system becomes independent of nuclear fuels produced from natural uranium in about the year 1975. It should be noted that the fertile material (U^{238}) requirement is independent of breeding gain.

Similar data for the aqueous thermal breeder system are shown in Fig. 4. In this case, the breeding gain is assumed to be 0.1, giving a fuel doubling-time of 5.5 years. Higher breeding gains reduce this doubling time and the corresponding number of years before the system becomes independent of fuel produced from natural uranium.

In the case of converter reactors, the fuel requirement due to burnup becomes an important factor. This depends on the efficiency with which neutrons are captured by U^{235}. In this reactor, this is commonly measured by the initial conversion ratio (grams of fuel produced per gram of U^{235} burned in fresh material). As the plutonium concentration and fission-product poisons build up in the reactor the conversion ratio falls off, and eventually the reactor must be reloaded with fresh fuel. Since the relation between the initial conversion ratio and total uranium utilization depends on specific reactor characteristics, estimates of this relationship vary widely. It can be shown, however, that approximately 10 tons of natural uranium are required per billion kwh for an initial conversion ratio of 0.85 and 3 tons per billion kwh for an initial conversion ratio of 1.00. Assuming the same inventory requirements for both types of converters, the annual total requirements are shown in Fig. 5.* Data for the breeders are given for comparison. Integrating these curves gives the cumulative requirements shown in Fig. 6 for all reactor types. It is significant that the converter reactors require no more total material for the first 25 years of nuclear power than the breeder reactors, and never an order of magnitude greater amount. On this basis, it can not be said that breeders are necessary

TABLE 5—U. S. Fuel Reserves

Fuel	*Reserves (10^{18} Btu)**	
	Assured	*Ultimate*
Coal	7.6	25.4
Petroleum	0.2	0.4
Oil from shale	1.2	3.0
Natural gas	0.2	0.3
U and Th	150	

* 10^{18} Btu = $1Q = 4 \times 10^{10}$ tons of coal = 17×10^{10} barrels of oil = 10^{15} ft³ of natural gas = 17×10^3 tons of U or Th.

* G_3 = grams of nuclear fuel produced per gram burned at start of cycle = breeding gain + 1.

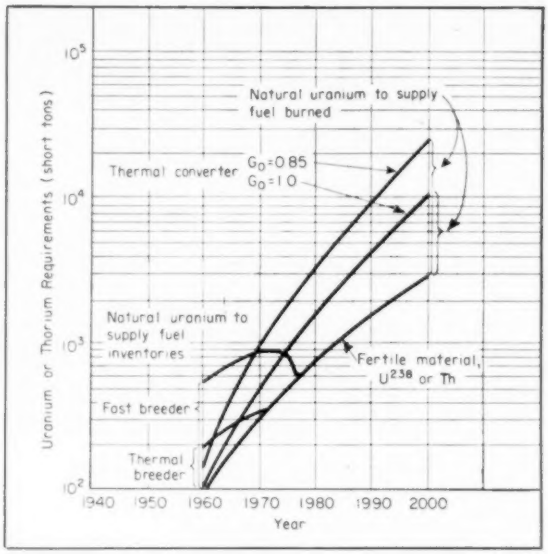
Natural uranium to supply fuel burned
Thermal converter G_0=0.85 G_0=1.0
Natural uranium to supply fuel inventories
Fertile material, U^{238} or Th
Fast breeder
Thermal breeder
Uranium or Thorium Requirements (short tons)
Year

FIG. 5. Annual fuel and fertile material requirements

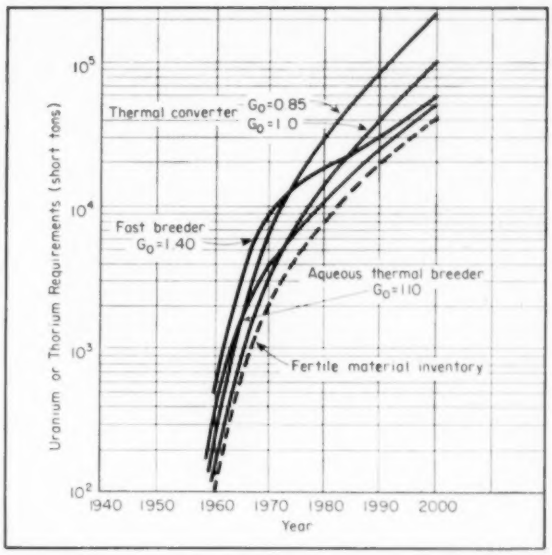

FIG. 6. Cumulative material requirements for all reactor types

to conserve our supply of reactor fuels.

The data in Figs. 5 and 6 serve not only to compare reactor systems, but also to give the approximate requirements of natural uranium or thorium in a large-scale nuclear-power industry. These requirements can be compared with our resources as shown in Table 5.

AEC's Division of Raw Materials has estimated that world resources of uranium and thorium, at prices less than $100/lb, amount to 25×10^6 tons and 1×10^6 tons, respectively. Projected requirements for U. S. industrial nuclear power during the next 50 years amount to less than one-half of 1% of the uranium, or 5% of the thorium reserves. On this basis it is apparent that there will be an adequate fuel supply for a large-scale industrial-power program.

Nuclear Power Contribution

Even if expansion of the nuclear power industry is as great as predicted, nuclear fuels will make a relatively small contribution towards solving our fuel supply problem. By 1980, the annual output of the nuclear plant system would be 2×10^{15} Btu compared to 2×10^{16} Btu for the total electrical industry (and 7×10^{16} Btu for the total power consumed in the U. S.). In the year 2000, nuclear plants would contribute about one-third of the total electric output (and about 10% of the total U. S. power). The integrated contribution of nuclear fuels for the 40-year period will amount to less than 5% of the total fuel consumed.

Equipment Industry

Although the total contribution of nuclear fuels to our power supply over the next 50 years might be small, the industrial output of equipment and special materials for the growth of a nuclear electric plant system will be significant. Table 6 gives the distribution of equipment, materials and construction costs for an average large-scale nuclear plant. By combining these data with the projected expansion curves, the potential annual investment in equipment is as shown in Fig. 1. It should be pointed out that costs for many parts of the plant will be the same, independently of whether the plant is nuclear-powered or coal-fired. The unusual features of nuclear power plants will generate formation of new kinds of industries, as well as expansion of those now existing. The production of special materials for reactors will, in particular, become a sizable industry in its own right.

TABLE 6—Nuclear Power Plant Cost Breakdown*

Components	*Cost ($/kw)*
Reactor structure and associated equipment (tanks, shields, gas handling equipment)	20
Heat removal and steam generation equipment (pumps, piping, heat exchangers)	35
Special materials (D_2O, graphite, zirconium, titanium)	30
Instrumentation and controls	5
Turbogenerator plant (turbogenerator, condensers, feedwater equipment)	70
Buildings and site facilities	40
Accessory electrical equipment (switchgear, transmission plant)	20
Total	220

* Basis: average large-scale plant (~500 Mw capacity), no development costs, reactor plant at $100/kw, turbogenerator plant at $120/kw. Depending on reactor type, equipment costs of some plants may deviate considerably from these average values.

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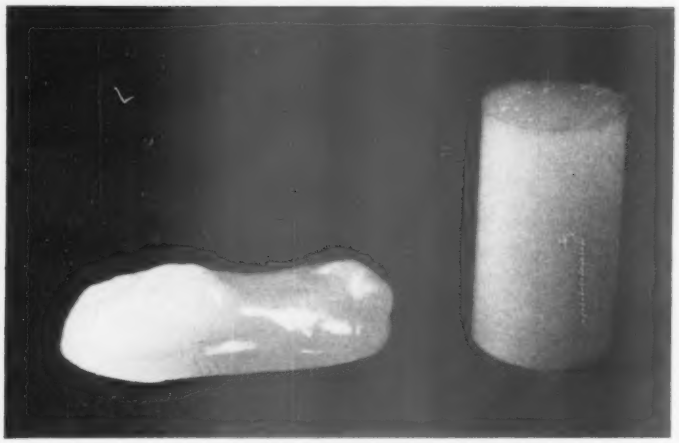

FIG. 1. Effect of irradiation on heat-resistant (120° C) properties of polyethylene. Control sample at left; shortly-irradiated sample at right

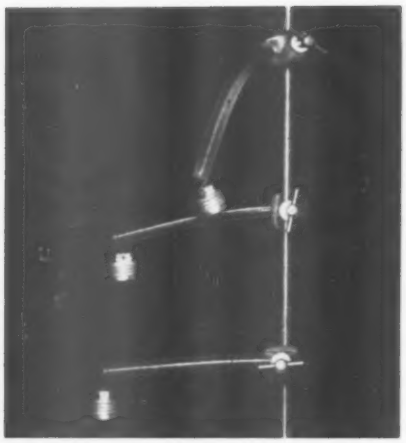

FIG. 2. Elastic properties of irradiated polyethylene at 150° C. Top rod had received 0.6 units irradiation; middle rod, 3 units; bottom rod, 12 units

How Radiation Affects Long-Chain Polymers

Data showing effects of radiation-induced crosslinking or degradation of plastics indicate that the effects can be used in polymer research and for industrial processes. Rough cost estimates define commercial feasibility

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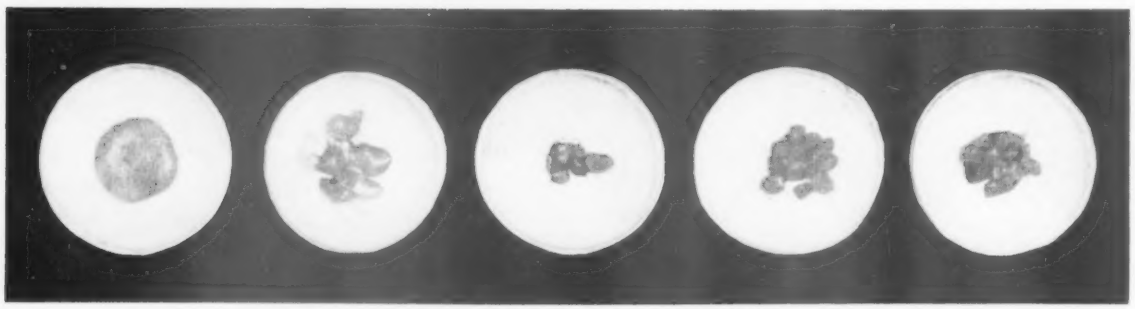


FIG. 3. Transformation of polyethylene from a melting to a non-melting polymer at 190° C. Samples held at temperature for 1½ hours. From left to right, samples received 0, 0.04, 0.05, 0.09, and 0.14 units of radiation

PROPERTIES OF MANY long-chain polymers can be modified considerably by exposure to high-energy ionizing radiation. The changes are far greater than those produced when most nonbiological materials are exposed to a similar amount of radiation, since a change of only one chemical bond of many hundreds can profoundly influence a material's physical properties even though the chemical structure is affected very little.

This article is concerned with the behavior of irradiated long-chain polymers of the thermoplastic type. The effect of radiation on polymerization of unsaturated monomers and on thermosetting resins of the urea-formaldehyde type is not considered.

Long-Chain Polymers

Long-chain polymers consist of molecules of varying length that contain a large number of repeating units known as monomers. The monomers are linked together in each molecule to give a long chain skeleton that usually, but not always, contains carbon atoms. Attached to the skeleton are side chains, which in the simplest case (polyethylene), are hydrogen atoms; but they often comprise more complex chemical groupings.

The main chain itself is not always linear. Branched side chains also may be present. In any one specimen the molecules are usually of different lengths. One of the basic problems of polymer science is to determine the average length and distribution of chain lengths about this mean. These factors greatly affect the properties of the resultant plastic.

In spite of their great length, long-chain polymers consist of separate molecules held together by weak Van der Waals forces. Thus, they can melt, flow, or be dissolved without altering the molecular structure itself. In this respect they differ from the thermoset plastics, which contain a three-dimensional network between the reacting chemical groupings. Such a network cannot be broken without permanently fracturing some of the primary bonds.

Radiation Effects

Exposure of thermoplastics to radiation produces crosslinks or degrades the main or side chains (*1–3*).

Permanency of change. Unlike the effect of radiation on other solids (such as metals), once produced, changes in plastics are as permanent as the bonds in the original material. When radiation removes an atom from its molecule, the atom is extremely unlikely to find an equivalent position in which it can settle in the structure. Thus, permanent changes are produced in the chemical bonding. These changes are usually accompanied by removal of the displaced atoms in the form of a gas.

Extensive effects. The number of bonds affected is considerably greater than the number of primary collisions with the incident high-energy particles. A fast neutron may provide energies of the order of 10^5 ev per collision. In certain polymers, this is sufficient to produce 5×10^3 bond changes at 20 ev each. Thus, the process often can be relatively economical as far as conversion of energy to chemical change is concerned. For example, in polyethylene an additional bond per 2,000 carbon atoms will greatly change the properties of the material. One collision with a fast neutron can produce marked differences in the behavior of some five thousand molecules containing a total of about six million carbon atoms.

A summary of many of the effects produced by ionizing radiation on a number of polymers is given in the following sections. A given polymer was chosen for study, not because of any fundamental difference in its behavior, but mainly because it most clearly showed the property under investigation or because certain constants for the material were available. Irradiation was usually carried out in the BEPO reactor (*4*) or close to a Co^{60} gamma source. Linear accelerators and X-ray machines have also been used.

In BEPO exposures, the radiation unit referred to in the following sections corresponds to an integrated flux of 10^{17} slow neutrons cm^2 plus associated fast neutrons and gammas. For many polymers that contain only carbon and hydrogen, this unit produces the same effect as an exposure to 50-million roentgens of pure gamma radiation.

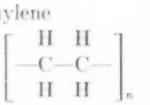
CHAIN CROSSLINKING

The individual molecules in polyethylene, polystyrene, and rubber are linked together by chemical bonds

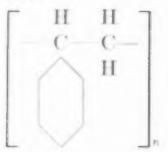
How Radiation Affects Polymers

CROSSLINKS

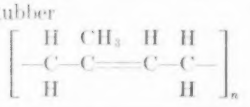
Polyethylene



Polystyrene

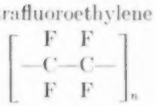


Rubber

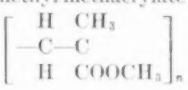


DEGRADES

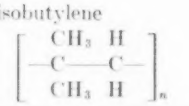
Polytetrafluoroethylene



Polymethyl methacrylate



Polyisobutylene



Uses of Radiation Effects

In certain polymers, the transition from solid crystalline to amorphous structures can be investigated. This throws light on the nature of the solid state. Exposure to radiation provides a physical means of crosslinking in which the degree of crosslinking can be controlled accurately without use of chemical agents or heat treatment.

Thus, a valuable new tool is available for study of polymer systems and more orthodox organic chemical structures. For other polymers, controlled degradation can produce a known molecular-weight distribution. On the practical side, this effect offers possibilities of producing new plastics or modifying old treatment techniques (such as vulcanization of rubber).

Many of the basic radiation effects can be studied most readily by using the simple polymers; but changes also can be produced readily in more complex polymers and in copolymers. Bombardment with high-energy electrons has produced polyethylene bottles that can be sterilized (16).

whose formation is induced by radiation. The crosslinking profoundly affects melting and solubility.

Polyethylene

At room temperature polyethylene has a white appearance reminiscent of paraffin wax, to which it has a certain chemical analogy (apart from molecular length). It can be cold-drawn. It begins to soften at about 70° C, and becomes a viscous transparent liquid at about 115° C. It is readily soluble in many organic compounds at temperatures of about 80° C. These properties are a serious disadvantage in many applications.

During irradiation, polyethylene can be crosslinked readily, and primary bonds can form between adjacent carbon atoms (*5*). After a radiation dose of about 0.05 units or 2-million roentgen (amount depends on molecular weight) it no longer melts, because it is transformed partly into a three-dimensional network. This effect is shown in Fig. 1.

After irradiation up to 1 unit there is no obvious change in the physical properties at room temperature; after doses up to 10 units it becomes progressively more flexible; above this it stiffens again and may transform into brittle glass-like material. In this region it is almost entirely amorphous, even at room temperature. It develops a strong yellow or brown tint similar to that observed in many polymers after irradiation.

By irradiation of specimens under certain conditions for about 4 units, polyethylene can be converted into a new type of polymer that is flexible, amorphous and largely transparent at room temperature. The amorphous character is retained down to very low temperatures. This material is so very different from the more usual polyethylene that a new name, "setylene," might well be used to emphasize its thermoset character.

Melting. It is misleading, perhaps, to refer to a radiation-produced rise in the melting point if by this is meant the removal of crystallinity. In ordinary polyethylene, the molecules are bound together largely by Van der Waals forces in the crystalline regions, which comprise about two-thirds of the specimen at room temperature. When these melt, the solid polymer is converted to a liquid. Radiation does not increase the melting point of these crystalline regions—instead there is a slight decrease (*6*). The crosslinks produced by radiation hold the molecules together even when crystallinity is destroyed above 115° C. The irradiated polymer then is transformed into a flexible amorphous material that has certain rubber-like properties as shown in Fig. 2.

The melting properties of slightly irradiated polyethylene are shown in Fig. 3. Small cubes were placed in the reactor, irradiated to varying extents, and then were heated to 190° C for 90 min. The unirradiated cubes fused together into a liquid that subsequently solidified to the shape shown. The same was true of polyethylene irradiated for varying dosages up to about 0.04 or 0.05 units, though to a less marked extent because the small amount of crosslinking that had occurred increased the average molecular weight sufficiently to produce a very viscous liquid that did not flow readily. Longer irradiations prevented the cubes from fusing together and they could be separated readily.

The transition at about 0.05 units of radiation corresponds to about 0.5 crosslinks per molecule. This figure is lower than the minimum that might be expected (namely one crosslink per molecule) for gel formation. The low transition occurs because the molecules are of different sizes and the longer molecules have a greater chance of having at least one crosslink. These longer molecules link to form a nonfusible network that retains the shorter molecules that have not been crosslinked. The shorter molecules can be

"Memory" Effect

An interesting property of lightly-irradiated polyethylene can be referred to as the "memory" effect. If the polymer is crosslinked very slightly (about 1.5 crosslinks per molecule) and then heated above the usual melting point, it is extremely flexible and can be deformed very considerably. If this modified shape is cooled, crystallization occurs and the molecules become locked in their new position. The specimen then resembles polyethylene molded into this new shape. However, on reheating the specimen above the melting point, the crystallites melt and the few crosslinks present return the specimen to its original shape. The process can be repeated any number of times, and the time of storage in the distorted form is irrelevant.

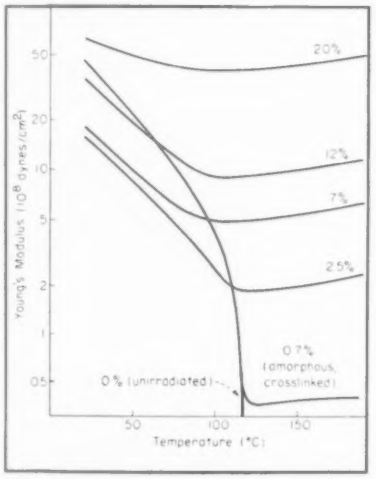


FIG. 4. Elastic properties of irradiated polyethylene. Percentages give proportions of carbons crosslinked

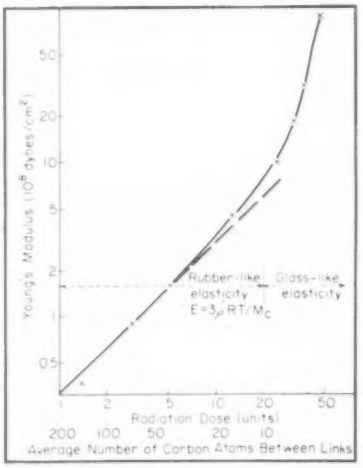


FIG. 5. Elastic properties of amorphous polyethylene at 150° C

removed from the network by solubility tests.

Elastic properties. Figure 4 shows the change in elastic properties of polyethylene after various irradiation doses (7). At first there is a drop in Young's modulus until the usual melting point is reached (about 115° C). Unirradiated polyethylene becomes a viscous liquid. Irradiated polyethylene is transformed into a transparent and elastic material that is amorphous in character. The elastic properties above this temperature are found to follow the theoretical formula for amorphous rubber-like elasticity that has been deduced from entropy considerations

$$E = 3\rho RT/M_c$$

where E is Young's modulus, ρ is the density, R is the gas constant, T is the absolute temperature, and M_c is the average molecular weight between crosslinks. Since density of crosslinking is directly proportional to radiation dose, E is proportional to the degree of irradiation over a wide range of doses. The curves of Fig. 5 show that the formula fails only for very high crosslinking densities where elasticity corresponds to that of a glass-like structure.

Once crystallinity has been destroyed by radiation, the density of an amorphous structure can be determined in terms of both crosslinking density and temperature. The results can be expressed in terms of an equation very reminiscent of a simplified Van der Waals equation

$$(P + P_0)(V - V_0) = RT[1 - \beta(c)]$$

where P and P_0 are the external and internal pressures, V is the volume of polyethylene per gram mole of C_2H_4, and V_0 is the volume at 0° K. The term $\beta(c)$ is a function of the degree of crosslinking c, and approximates to c (the proportion of carbons crosslinked).

This equation of state applies approximately to other crosslinked polymers in the amorphous state.

Solubility. The solubility characteristics of many long-chain polymers are affected considerably by radiation.

Ordinary polyethylene is readily soluble in many organic materials at temperatures above 70° C. A very slight amount of crosslinking (corresponding to less than 0.03 units of radiation) does not greatly affect this property, since molecules are only linked together in small numbers to alter the molecular weight distribution. A somewhat larger radiation dose (about 0.05 units), corresponding to about 0.5 crosslink per molecule, links a large number of molecules together into one large molecule or gel that is insoluble in all usual organic solvents. The remainder of the specimen (the molecules that have not been linked into the structure) can still be removed by solvents, but the amount of this soluble fraction or sol is limited. Further irradiation gives a rapidly decreasing amount of soluble material. From the relationship between the sol fraction and the radiation dose, useful information can be derived as to the molecular weight distribution in the original polymer.

In solvents, crosslinked polyethylene swells to an extent that depends on its temperature and degree of crosslinking. Considerable swelling can be produced in lightly-linked specimens at temperatures above the usual melting point.

Other paraffinic structures. The effect of radiation on other paraffinic structures has also been studied (*8*). Paraffin wax and paraffin molecules of known molecular weight from heptane (C_7H_{16}) to hexatriacontane ($C_{36}H_{74}$) in both liquid and solid state have been successfully crosslinked into an infusible gel. The amount of radiation required to do this is inversely proportional to the molecular chain length. In all cases the energy absorbed is about 25 ev per crosslink.

Polystyrene

Insolubility of the product and changes in the softening point show that polystyrene can be crosslinked by ionizing radiation. Radiation doses to achieve these effects are far greater than for polyethylene despite the much larger number of monomer units in the average polystyrene molecule. For example, a polystyrene molecule containing an average of about 8,000 carbon atoms in the main chain of the molecule requires 1 unit of radiation per crosslink, whereas a polyethylene chain of the same chain length would only need about 0.02 units to achieve the same amount of crosslinking. The difference can be ascribed to the benzene ring in styrene. Such a ring stabilizes many organic compounds against the effects of radiation. The resonant levels of the benzene structure act as a sink and dissipate the added energy that otherwise might produce crosslinking or degradation.

It can be shown directly that the stabilizing effect is due to the resonating benzene ring. Molecules consisting of either a naphthyl or decalyl ring structure to which similar paraffinic side chains are attached, have been irradiated. The former, which has a resonant structure, requires far more radiation to induce gel formation than the latter, although there is no significant difference in the rate of energy absorption by the two types of molecule.

Surface oxidation. As in polyethylene, surface oxidation occurs when polystyrene is irradiated in the presence of air. After considerable irradiation, a brown powder is formed that contains substantial amounts of oxygen. Unlike the oxidation product on the surface of polyethylene, this material is not sticky and can be removed readily. Apart from this slight oxidation the only obvious change to irradiated polystyrene rods is a yellow coloration that increases rapidly with radiation dose.

Melting. Figure 6 shows how irradiated polystyrene rods withstand high temperature. In spite of the slightness of crosslinking, the irradiated specimens retain their shape and do not melt or flow when heated to 250° C. At the same temperature, the unirradiated specimen forms a viscous liquid. For a radiation dose (0.6 units) corresponding to only 0.6 crosslinks per molecule (1 crosslink per 6,000 carbon atoms) there is a marked effect in the melting character of the polymer. It would be expected that at least 1 crosslink per chain is needed to obtain an infusible network. However, the wide variation in chain lengths means that most of the longer molecules will contain at least one link and will form a network that can withstand the high temperature while retaining the shorter molecules within itself.

Solubility. Results obtained on solubility and swelling of crosslinked polystyrene are of considerable interest in polymer research (*9, 10*).

For a small amount of radiation and crosslinking, the molecular weight distribution is altered with a corresponding change in the viscosity of the product when dissolved. For such radiation doses certain molecules be-

come linked together in pairs, threes, etc. As radiation dose is increased, a point is reached where a network of theoretically infinite extent is formed that includes a large number of the original molecules linked together into one gigantic molecule. By definition, this is insoluble and is referred to as the gel. Molecules not linked into this structure are still soluble and form the sol fraction. With further radiation and increased crosslinking, the gel fraction increases while the sol fraction diminishes. It can be shown that if only crosslinking occurs, the soluble fraction tends to zero with increasing radiation dosage, whereas, if some degree of random main chain fracture also is produced, the sol fraction tends to a finite amount characteristic of the ratio of chain fracture to chain crosslinking. For polystyrene, the curves of Fig. 7 indicate that little or no main chain fracture occurs under radiation.

Several theoretical studies have been made of the variation of gel fraction with crosslinking density—the latter being accurately proportional to radiation dose. The relation is found to depend on the initial molecular weight distribution. Experimental measurements of the gel fraction in polystyrene crosslinked by pile radiation have been combined with this theory to obtain information on this molecular weight distribution.

Irradiated polystyrene also has been used in connection with studies of swelling of crosslinked polymers. A crosslinked polymer will swell in compounds that are usually solvents for the uncrosslinked molecules. The solvent molecules (benzene, toluene) enter the network and try to force the molecules apart. This tendency is resisted by the elastic properties of the crosslinked network. With higher degrees of radiation (and, hence, of crosslinking) the swelling is reduced.

An approximate theory of this effect has been worked out (*11*). Irradiation provides the polymers of varying and known degrees of crosslinking that are necessary for full experimental analysis. Figure 8 shows that the theory is remarkably accurate over a wide range of degrees of crosslinking, in spite of several approximations made in the theoretical relationships. For example, the theory does not allow for the existence of a soluble fraction nor for the difference in crosslinking between gel and sol (the gel will tend to contain a higher proportion of crosslinked polymers). A detailed analysis shows that the errors due to these various factors tend to cancel each other out so that the excellent agreement observed is to some extent fortuitous.

By calibrating the swelling of a series of polymers crosslinked by irradiation it should prove possible to provide laboratory standards of crosslinking for use in industrial and research laboratories dealing with polymer behavior.

Rubber

Rubber can be considered a naturally occurring polymer that, for most practical purposes, has to be vulcanized (crosslinked). This crosslinking can be achieved by exposure to ionizing radiation alone, without introducing sulfur or accelerators and without heat treatment (*12*). The process can take place in the absence of oxygen, and Fig. 9 shows that the degree of crosslinking is proportional to the radiation. The efficiency of crosslinking (number of monomer units crosslinked per unit radiation) is somewhat higher for rubber than for polyethylene. Crosslinking efficiency can be deduced both from swelling experiments and from the network's elasticity.

Experiments on the gelation of rubber by radiation have been carried out to determine the changes in molecular weight produced by crosslinking; these may be followed approximately by studying the viscosity of the soluble fraction. An alternative method is based on measurements of gel fraction for various radiation doses. Both sets of data give similar values for the initial average molecular weight of the rubber; it should prove possible to use these techniques to obtain information on molecular weight distribution. The results already obtained amply confirm the theory of gelation and the assumption of random crosslinking.

The technique of using radiation to crosslink oriented structures might have useful industrial applications. If specimens of rubber are stretched and irradiated in an oriented form, they

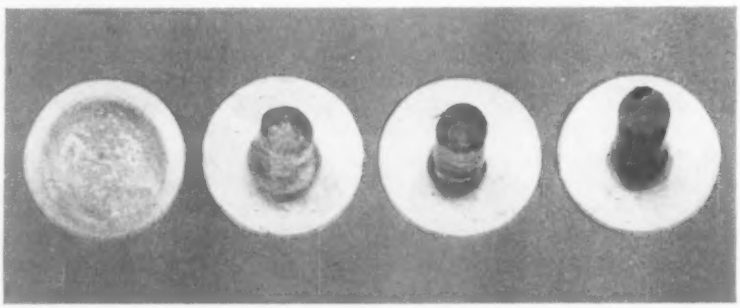


FIG. 6. Effect of heat on irradiated polystyrene. From left to right, samples received 0, 0.6, 2, and 6 units of radiation. All samples were heated at 250° C for 30 minutes

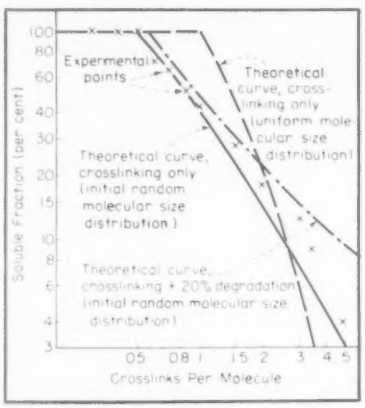


FIG. 7. Solubility decrease of irradiated polystyrene

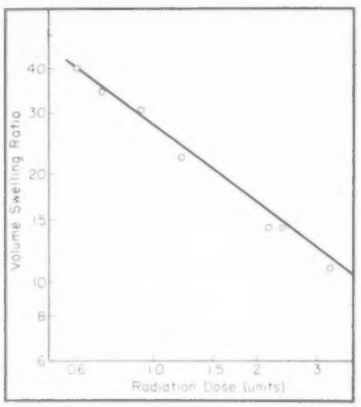


FIG. 8. Decrease in swelling in toluene of polystyrene crosslinked by radiation

will retain this orientation. The material produced will have different properties parallel and perpendicular to the direction of stretch.

Other Polymers

Numerous other long-chain polymers can be crosslinked by high-energy radiation; these include Nylon, polyvinyl acetate, polyvinyl alcohol, gutta percha, and Neoprene. Nylon, for example, becomes far more brittle and is less extensible after irradiation. With an adequate amount of crosslinking, creep largely can be suppressed.

The property of crosslinking is not confined to long-chain polymers with carbon atoms in the main chain. Figure 10 shows how lubricating oil solidifies. Silicones have been successfully crosslinked, the amount of radiation required being smaller for the longer molecules, as is to be expected if crosslinking occurs at random. The crosslinked polymer formed is transparent and does not flow even at fairly elevated temperatures.

CHAIN DEGRADATION

The individual molecules in polytetrafluoroethylene, polymethyl methacrylate, polyisobutylene, and cellulose are degraded by high-energy radiation. The changes have varying effects.

Polytetrafluoroethylene

The essential difference between this polymer and polyethylene consists in the substitution of fluorine for hydrogen atoms on the carbon atoms of the main chain. The inert character of PTFE can be ascribed to the strong bond between the fluorine and carbon atoms.

If the crosslinking of polyethylene is due to the breaking of C-H bonds and the removal of hydrogen having active carbon atoms that can crosslink, it is to be expected that the possibility of crosslinking in PTFE will be diminished greatly by the high stability of the C-F bonds. This behavior is, in fact, observed. On irradiation, PTFE tends to break up, and gases (particularly CF_4) are released (*13*). Energy absorbed in the molecules breaks the C-C bonds in the main chain rather than the stronger C-F bonds.

Figure 11 shows that after 10 units of radiation, solid blocks of PTFE decompose to a coarse powder. Thin layers of the same material are more resistant. A detailed analysis (based on weight changes during irradiation) shows that weight losses are proportional to the surface area and to the square of the radiation dose.

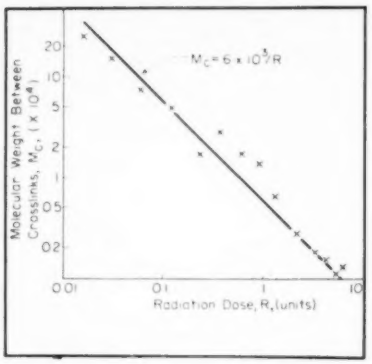


FIG. 9. Effect of radiation on crosslinking of rubber

These results are consistent with the hypothesis that chain fracture occurs at random, producing groupings the shortest of which are eventually evolved as CF_4, provided they are produced close to the surface. Similar gases produced deeper within the specimen cannot escape, and the internal pressure of these gases (together with the weakening due to the reduction of molecular weight arising from the fracture of the main chain) breaks the material into fragments.

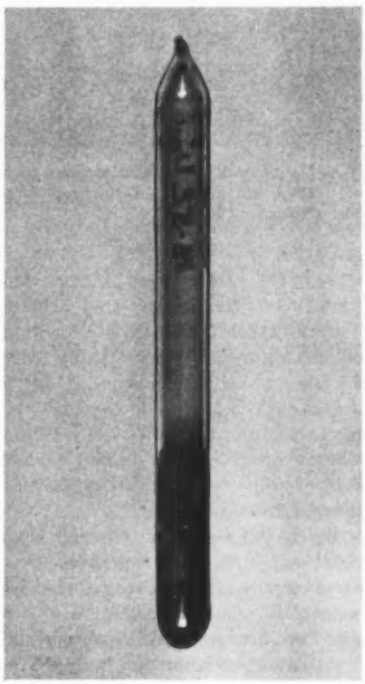


FIG. 10. Radiation-induced solidification (by crosslinking) of lubricating oil into a yellow, bubbled mass

The irradiated material softens at a lower temperature, and this may offer considerable processing advantages as compared with the more usual form of polytetrafluoroethylene.

Polymethyl Methacrylate

Polymethyl methacrylate shows most strikingly the degradative effects produced on the main and side chains by exposure to high-energy radiation (*14*, *15*).

When exposed to small radiation doses (of the order of 0.5 units or less) specimens of the polymer in the form of rods or blocks appear to be almost unaffected; the only obvious physical changes are a slight yellow coloration and an increased brittleness. After irradiations of the order of one unit at about 80° C., the polymer swells into a foam or mass of bubbles consisting mainly of hydrogen, carbon monoxide and carbon dioxide, which are the main breakdown products of the side chain. Increases in volume of the order of eight times can be produced.

Figure 12 shows that if irradiation is stopped before the foaming stage is reached, and the specimen is subsequently heated, the same process of foaming takes place. The higher the radiation dose, the lower is the temperature needed to produce this effect, at least for temperatures above about 70° C.

The explanation is that radiation produces side-chain fracture at random throughout the specimen, and the resultant gases are retained in the solid until a combination of increased pressure (due to the temperature rise) and weakened polymer structure cause bubble formation. Bubbles do not occur near the surface; the gases produced there can escape.

This behavior may be of interest in connection with research into the diffusion of gases in solids and the formation of nuclei. The process is, in some respects, analogous to the formation of bubbles in boiling liquids; but it has the advantage (from the point of view of the investigator) that it takes place more slowly and can be stopped at any stage by sudden cooling.

Viscosity measurements of irradiated material give a measure of the molecular weight of the polymer. Molecular

weight is found to decrease rapidly with radiation dose as

$$M_v = K/(R + R_0)$$

where M_v is the viscosity average molecular weight (deduced from viscosity measurements), K is a constant, R is the radiation dose and R_0 is a small correction factor that can be considered as the "virtual" radiation dose needed to produce the initial molecular weight from an infinite chain. Therefore, measurement of viscosity appears to offer an extremely convenient means of estimating radiation doses of from 1-million roentgens upwards. All that is required is to irradiate a small piece of Perspex, dissolve it in a suitable solvent, and measure the viscosities of various concentrations at a given temperature. This method of measuring intrinsic viscosity is used often in polymer science and can give very reproducible results. The irradiated specimen may be kept for considerable periods before testing.

The two processes of side-chain and main-chain degradation are closely related, each main chain fracture being associated with the decomposition of approximately one side chain. The energy required per main-chain fracture is about 60 ev. Main-chain fracture takes place uniformly throughout the specimen; the absence of a surface effect is demonstrated by viscosity measurements. On the other hand, bubbling does not take place at a distance of about 1 mm from the surface. It has been shown that this is due to the evolution of the gas produced by side-chain fracture and that this process takes place during irradiation. The gases produced by irradiation can be retained in the polymer for considerable periods prior to bubbling by heating.

One can envisage a possible use for this irradiated polymer for heat insulation purposes. Blocks of irradiated polymethyl methacrylate could be placed around the vessel to be insulated. When heated, bubble formation would occur and insulating material would be produced *in situ*. The absence of bubbles in the outer layers would result in a material having a tough skin.

Polyisobutylene

Polyisobutylene has methyl groups replacing some of the hydrogen atoms in polyethylene. It degrades rapidly when irradiated and can be converted readily to a viscous liquid. At first thought this is surprising because we would expect hydrogen atoms to be evolved and, thus, active bonds to be made available for crosslinking. Diffraction data show that the molecular chain in polyisobutylene is arranged very differently from that in most long-chain polymers, probably due to steric hindrance of the relatively large side groups. Therefore, the main chain is in a state of strain, and this weakness renders it more liable to fracture under radiation.

APPLICATIONS

The fields in which use of high-energy radiation can be applied to produce changes in long-chain molecules appear to be considerable.

Polymer research. It is possible to use radiation to produce polymers (crosslinked to any required extent) and study their properties as a function of the degree of crosslinking. By using small radiation doses, a known degree of chain branching can be produced, and the effect of this on viscosity, softening or melting points, elastic properties, etc., then can be investigated quantitatively.

Where radiation-induced chain degradation occurs, it becomes possible to produce polymers of known molecular weight and of a given molecular weight distribution (namely, that corresponding to random chain fracture). This method has already been used to study the relationship between viscosity molecular weight and intrinsic viscosity for polyisobutylene and polymethyl methacrylate.

A further field is in the quantitative study of the ability of various types of bonding to resist the effect of high-energy radiation. The influence of the benzene ring in polystyrene has been mentioned, and other structures are being studied. This is of particular interest in such fields as copolymerization and in studies of the role played by sulfur and carbon black in rubber vulcanization.

The process is not limited to long-chain polymers. It can be used to modify the properties of shorter molecules, such as those present in oils, although the radiation doses needed are much greater.

The method also can be applied to biological systems. A fuller understanding can be expected only when studies of simpler long-chain molecules (in which the chemical and physical structures are known) permit making useful predictions of the mechanism of radiation effects.

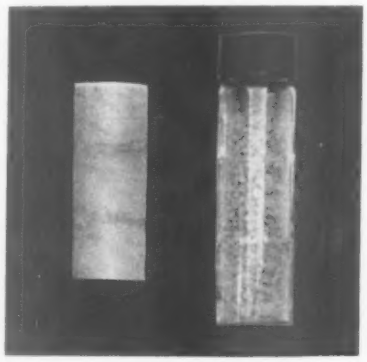


FIG. 11. Radiation-induced degradation of a solid rod of polytetrafluoroethylene into a coarse powder

FIG. 12. After the slightly irradiated rod of polymethyl methacrylate (left) has been heated to about 120° C, it is expanded by bubble formation

Commercial possibilities. Apart from its use in research work, the possibility of producing crosslinked, degraded, and foamed material under accurately controlled conditions by a purely physical process can well have valuable commercial possibilities. In the long run, these will depend on the cost of irradiation, the enhanced value of the material, and the comparative cost of the competitive chemical process (where one is available).

There are two stages in which the process can be introduced. In the

first stage, specialized materials of high intrinsic value when treated will be processed on a limited scale. Particularly, this method will be used to treat materials whose properties cannot readily be suitably modified by other techniques. In the second stage, irradiation may be in direct competition with existing chemical techniques. The time scale will be determined mainly by the availability and comparative costs of the various methods of obtaining high-energy radiation.

Sources. Since the phenomena observed occur equally well whatever the source of primary high-energy radiation (electrons, X-rays, γ-rays, fast neutrons, etc.), the most suitable form of radiation will depend on the cost of the source and its ability to produce radiation of the most useful penetrating power. High-energy electrons obtained from linear accelerators have penetrations of only a few millimeters and, thus, seem most suitable for thin specimens. Gamma radiation is so penetrating that fairly considerable thicknesses of material are necessary if full use is to be made of the energy available. The use of reactors appears feasible. Irradiations can be carried out in the shield, thus making use of energy otherwise wasted. However, installation of conveyor belts or similar methods of feeding specimens into reactors, and post-irradiation storage in the immediate vicinity of the reactor might raise engineering objections.

Economics. Use of high-energy radiation on a commercial scale appears to be promising in a number of fields. In many cases the required radiation doses run into at least several million roentgens. It is too early to make any reliable calculations of costs, but very rough estimates concerned with the use of fission products may be of interest as an order-of-magnitude indication.

Assume that fission products will be available at d dollars per curie (including cost of installation and operation) and have a half-life of y years. Furthermore, consider a radiation treatment needing r million roentgens, and consider that the plant is designed to have an efficiency η (i.e., the proportion of emitted radiation captured by the irradiated specimens). A gamma source of 10^5 curies, emitting γ-rays of E Mev, will emit $(3.7 \times 10^{10} \times E \times 10^6 \times 10^5)$ ev/sec, or $(2.3\ E \times 10^9)$ ergs/sec. This is equivalent to about $(3\ E \times 10^7)$ roentgen/sec for the materials generally dealt with, and will process $(30\ E\eta/r)$ gm/sec, or about $(1{,}000\ E\eta/r)$ tons/yr in full operation. The cost of treatment will be $10^5\ d/y$, or $(100\ dr/yE\eta)$ per ton.

For example, if we assume an installed and operating cost of \$1/curie ($d = 1$), a treatment needing 1-million roentgens ($r = 1$), a source of half-life 10 years ($y = 10$), a gamma source emitting 1-Mev γ-rays ($E = 1$), and an over-all efficiency of 10%, the cost of processing will be \$100/ton, or 5¢/lb.

This estimate is very rough indeed; somewhat higher radiation doses are needed for many polymers. About 2- to 3-million roentgens are required to initiate gel formation in many types of polyethylene. The cost of producing, installing, and operating fission-product sources is not known, nor is the efficiency with which radiation can be absorbed. However, these figures indicate that costs are not necessarily exhorbitant for certain modifications in plastics.

In the cases of oils or shorter chain compounds in which several units of pile radiation are needed to produce useful changes, the costs are much higher. Two units of reactor radiation (or 100-million roentgens) would, on these bases, cost about \$5/lb. It is for this reason that the more promising commercial applications of crosslinking lie in the field of long-chain polymers. This is where small degrees of crosslinking result in marked and often desirable changes in physical properties.

A considerable need for sources of high-energy radiation appears to be arising for a variety of industrial purposes. Design of equipment to provide such sources at an economical cost is most desirable. The modification of polymer properties is only one of the possible applications of such sources. They also could be used for sterilizing pharmaceuticals and foodstuffs.

Next month in NUCLEONICS . . .

"A New Reactor Concept"

. . . an analysis of several years' study and experimentation aimed at conceiving a power reactor that can vie with other proposed reactors as the nuclear power plant of the future. Seven articles will consider possible designs for a homogeneous liquid metal fuel reactor, physics and metallurgy of fuels and breeder blankets, heat exchange, corrosion, reactor processing loops, and methods for continuous purification of fuel and removal of bred material.

CONCLUSIONS

The ability to crosslink or degrade long-chain polymers by high-energy radiation (under accurately controllable physical conditions) offers many interesting lines of research. The amount of information obtained to date is limited mainly by the effort devoted to this interesting new subject. Large-scale industrial use depends on the availability of suitable sources of radiation. The many applications possible can be discovered best by close collaboration between industrial scientists and radiation physicists and chemists.

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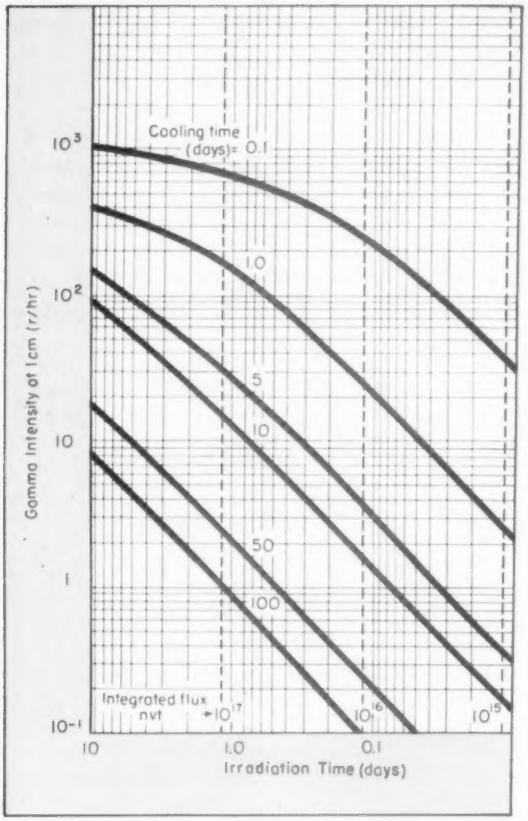

FIG. 1. Beta activity from 1 gm of natural uranium irradiated at 10^{12} n/cm²/sec

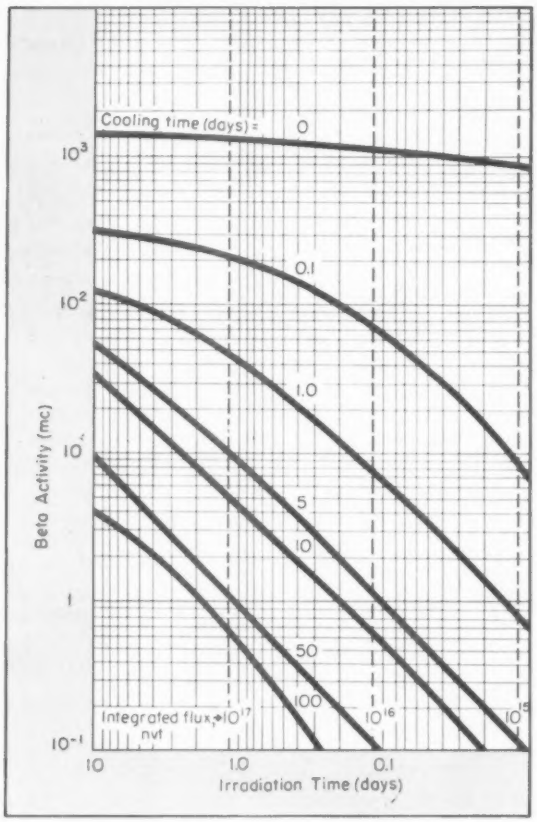

FIG. 2. Gamma intensity from 1 gm of natural uranium irradiated at 10^{12} n/cm²/sec

Estimating

Radioactivity of Irradiated Uranium

Graphical methods simplify evaluation of radiological hazards involved in handling irradiated uranium. Curves showing radioactivity of fission products and of plutonium permit estimates accurate within a factor of two

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CHEMICAL PROCESSING experiments frequently require a variety of reactor irradiations of uranium. To evaluate the radiological hazard involved in manipulating these specimens, and thus to plan a safe experimental procedure, it is necessary to estimate the beta activity, gamma radiation, and plutonium yield for each specimen. These calculations are facilitated by use of relatively simple graphs evolved by suitable empirical approximations.

Fission Rate

The fission rate in a given amount of U^{235} is

$$R = \sigma\phi n \text{ fissions/sec} \qquad (1)$$

where σ = capture cross section of U^{235}, ϕ = neutron flux, n = number of atoms of $U^{235} = (w \times 6.02 \times 10^{23})/235$, and w = grams of U^{235}.

For convenience, calculations have been made using $w = 1$ gm of natural uranium (0.00719 gm of U^{235}), $\phi = 10^{12}$ n/cm²/sec, and $\sigma = 549 \times 10^{-24}$ cm² (*1*). Thus

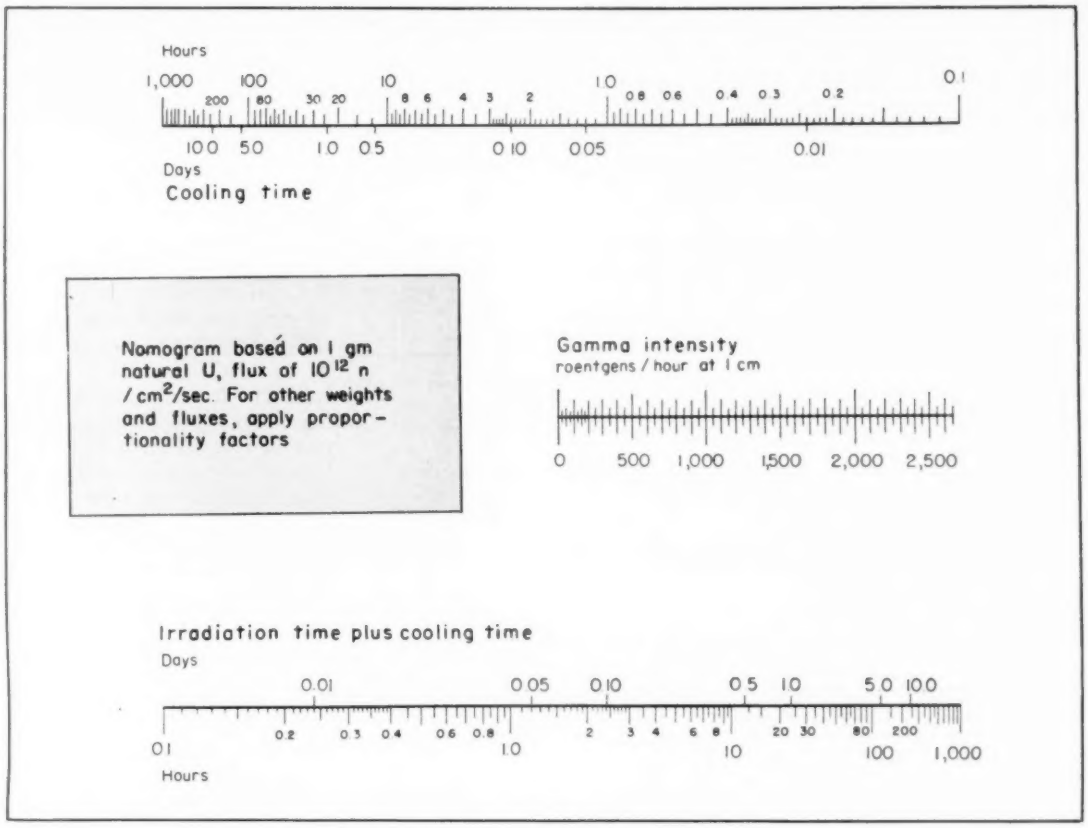
Hours
1,000 100 10 1.0 0.1
200 80 30 20 8 6 4 3 2 0.8 0.6 0.4 0.3 0.2
100 50 1.0 0.5 0.10 0.05 0.01
Days
Cooling time
Nomogram based on 1 gm natural U, flux of 10^12 n /cm^2/sec. For other weights and fluxes, apply proportionality factors
Gamma intensity
roentgens / hour at 1 cm
0 500 1,000 1,500 2,000 2,500
Irradiation time plus cooling time
Days
0.01 0.05 0.10 0.5 1.0 5.0 100
0.2 0.3 0.4 0.6 0.8 2 3 4 6 8 20 30 80 200
0.1 1.0 10 100 1,000
Hours

FIG. 3. Gamma intensity from 1 gm of natural uranium irradiated at 10^{12} n/cm²/sec

$$R = \frac{(549 \times 10^{-24} \times 10^{12} \times 0.00719 \times 6.02 \times 10^{23})}{235}$$

$$= 1.01 \times 10^{10} \text{ fissions/sec.}$$

In the solution of problems differing from those presented, the correct value of the number of fissions per second can be obtained by multiplying by suitable factors of proportionality. The corrected value R_1 for a given irradiation is

$$R_1 = \frac{\phi_1 w_1}{10^{12}} R = 0.010 \phi_1 w_1 \quad (2)$$

where ϕ_1 = flux for the reactor used, and w_1 = weight of natural uranium.

Beta Activity

The beta activity of unseparated fission products produced in irradiated uranium can be estimated (*2*). Although it would be more convenient to use the analytic development of Way and Wigner (*3*), the more accurate influence function, $\beta(a)$, of Thornton and Houghton (*4*) has been used in these calculations

$$C(T,t) = R \int_t^{T+t} \beta(a) da \quad (3)$$

where $C(T,t)$ = total beta activity of the fission products, R = fission rate of the U^{235} nuclei (assumed constant during T), T = irradiation time, and t = cooling time, $\beta(a)$ = disintegrations per second per fission as a function of time.

Figure 1 presents the beta activity in millicuries (3.7×10^7 dps = 1 mc) as a function of the irradiation time for various cooling times from 0 to 100 days. The fission rate, R, assumed for these calculations is 1.01×10^{10} fissions/sec.

The beta surface-dose rate can be calculated (*5*) as

$$D = 7.34 \times 10^{-6} NEQ \quad (4)$$

where D = dose rate, rep/hr; N = number of betas/hr/gm; E = energy loss per electron in air, Mev/cm; and Q = range of the electron in the source, gm/cm².

Assuming the average fission-product beta energy per disintegration is 0.4 Mev (*2*, p. 396), $N = 3.7 \times 10^7$ d mc/sec $\times$ 3,600 sec/hr $\times$ M mc/gm, $E = 2.5 \times 10^{-3}$ Mev/cm, and $Q = 0.12$ gm/cm², where M = beta activity, mc/gm (Fig. 1); and thus

$$D = 300\ M \text{ rep/hr.} \quad (5)$$

Gamma Activity

The gamma energy emitted per second for each fission-product nuclide as a function of time is

$$\Gamma_i = E_i g_i y_i R F_i(T,t) \quad (6)$$

where Γ_i = energy decay rate from ith nuclide, Mev/sec; E_i = gamma energy, Mev/gamma; g_i = fraction of disintegrations that yield gammas, gammas/nuclide; y_i = fission yield, nuclei fission; R = fission rate, fissions/sec; $F_i(T,t)$ = fraction of saturation activity of the ith nuclide irradiation; T = irradiation time, sec; and t = cooling time, sec.

Moteff (*6*) has evaluated the gamma energy from decaying mixed fission

products as the sum of the radiations emitted from 25 fission-product nuclides selected on the basis of high fission yield, high gamma energy (> 0.1 Mev) and long half-life (> 5 hr)

$$I = \Sigma\Gamma_i = R\Sigma E_i g_i y_i F \qquad (7)$$

The dose rate 1 cm from any radioactive point source is

$$D = \frac{\Gamma \text{ Mev/sec} \times 1.59 \times 10^{-6} \text{ ergs/Mev}}{4\pi \text{ cm}^2 \times \rho(E) \text{ ergs/cm}^2\text{/r} \times 3{,}600 \text{ sec/hr}} = \frac{4.55 \times 10^{-4}\Gamma}{\rho(E)} \text{ r/hr at 1 cm} \qquad (8)$$

where D = dose rate, Γ = energy emission from source, and $\rho(E)$ = energy flux per roentgen as a function of energy (7).

Therefore, the dose rate 1 cm from a point source of mixed fission products is

$$D = 4.55 \times 10^{-4}\Sigma \frac{\Gamma_i}{\rho(E_i)}$$

If an appropriate average energy, $E_{avg}(T,t)$, is assigned to mixed fission products, the dose rate 1 cm from a point source of mixed fission products is

$$D = \frac{4.55 \times 10^{-4}}{\rho(E_{avg})} \Sigma\Gamma_i$$

The average energy flux per roentgen, $\rho(E_{avg})$, has been evaluated using the nuclides selected by Moteff and is

$$\rho(E_{avg}) = \frac{I(T,t)}{D(T,t)} = \frac{\Sigma\Gamma_i}{\Sigma\frac{\Gamma_i}{\rho(E_i)}} \qquad (9)$$

For a large variety of irradiation and cooling times from 0.1 to 100 days

$$\rho(E_{avg}) = 2{,}760 \pm 90 \text{ ergs/cm}^2\text{/r} \qquad (10)$$

Therefore, the dose rate in r/hr at 1 cm from a point source of mixed fission products is

$$D = 1.65 \times 10^{-7}\Sigma\Gamma_i$$

Using the nuclides selected by Moteff, it would be possible to evaluate the dose rate from mixed fission products by the application of Eq. 10. It is more practical, however, to use an analytical expression (3) for the decay gamma energy as a function of time,

$$\Gamma(\tau) = 1.26\tau^{-1.2} \text{ Mev/fission/sec} \qquad (11)$$

This formula gives satisfactory agreement with experimental results, within a factor of two from a few sec to 100 days.

The delayed gamma energy, I Mev/sec, after irradiation for T seconds and cooling for a period of t seconds is

$$I = R\int_t^{T+t} \Gamma(\tau)\,d\tau = 1.26R\int_t^{T+t} \tau^{-1.2}\,d\tau = 6.3R\left[\frac{1}{t^{0.2}} - \frac{1}{(T+t)^{0.2}}\right] \qquad (12)$$

Therefore, the dose rate 1 cm from a point source of mixed fission products is

$$D = 1.04 \times 10^{-6}R\left[\frac{1}{t^{0.2}} - \frac{1}{(T+t)^{0.2}}\right]$$

Figure 2 presents gamma intensity in r/hr at 1 cm for continuous irradiation from 0.01 to 10 days for various cooling times. The fission rate, R, assumed for these calculations, is 1.01×10^{10} fissions/sec, and

$$D = 1.05 \times 10^{4}\left[\frac{1}{t^{0.2}} - \frac{1}{(T+t)^{0.2}}\right]$$

Figure 3 can be used to estimate the gamma radiation more accurately for periods not shown in Fig. 2.

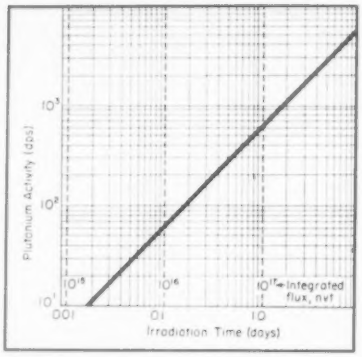

FIG. 4. Plutonium activity from 1 gm of natural uranium irradiated at 10^{12} n/cm²/sec

Plutonium Activity

The activity of Pu^{239} formed during irradiation of natural uranium is

$$A = \frac{\phi\sigma w 6.02 \times 10^{23}}{238} \times \frac{0.693T}{24{,}100 \text{ yr} \times 3.15 \times 10^7 \text{ sec/yr}} \qquad (13)$$

where A = activity of Pu^{239}, dps; ϕ = neutron flux; σ = capture cross section of U^{238}; w = weight of U^{238}, gm; and T = irradiation time, sec.

Figure 4 presents the activity of Pu^{239} in dps as a function of the irradiation time for $\phi = 10^{12}$ n/cm²/sec, $\sigma = 2.8 \times 10^{-24}$ cm² (1), and $w = 1$ gm. Thus $A = 6.5 \times 10^{-3}\,T$ dis/sec.

The specific activity of Pu^{239} is: 1 μgm of $Pu^{239} = 2.3 \times 10^3$ dps.

Example

Estimate the radiological hazards involved in manipulating 20 gm of natural uranium 10 days after it has received an integrated exposure of 10^{16} nvt in a flux of 10^{11} n/cm²/sec.

Beta activity. Irradiation time, $T = (10^{16} \text{ nvt})/10^{11} \text{ nv} \times 86{,}400 \text{ sec/day} = 1.16 \text{ days}$; cooling time, $t = 10$ days; weight of uranium, $w = 20$ gm.

Using Fig. 1 the beta activity is 5 mc, but the fission rate (from Eq. 2), is $R = 0.010 \times 10^{11} \times 20 = 2.0 \times 10^{10}$ fissions/sec. Since this is twice the rate used for the graphs presented, the beta activity is 2×5 mc = 10 mc. From Eq. 5 the beta surface dose rate is $D = 300 \times 10 = 3{,}000$ rep/hr.

Gamma activity. From Fig. 2, using the same fission-rate correction, gamma dose rate at 1 cm is 2×16 r/hr = 32 r/hr. To use Fig. 3, draw a straight line from the sum of the irradiation plus cooling times on left-hand scale through cooling time on right-hand scale. Read gamma intensity on center scale.

Plutonium activity. From Fig. 4, using the fission-rate correction factor, the Pu^{239} activity is

$$2 \times 650 \text{ dps} = 1{,}300 \text{ dps}$$

$$\frac{1{,}300 \text{ dps}}{2{,}300 \text{ dps/μgm}} = 0.57 \text{ μgm}$$

Although the curves have been drawn for 1 gm of natural uranium in a flux of 10^{12} neutrons/cm²/sec, simple proportionality factors can be used for irradiations of any mass in any flux.

The approximations used yield results that are believed accurate within a factor of two. No corrections have been made for the absorption and scattering of neutrons and gammas by the sample or for changes of cross section with temperature.

* * *

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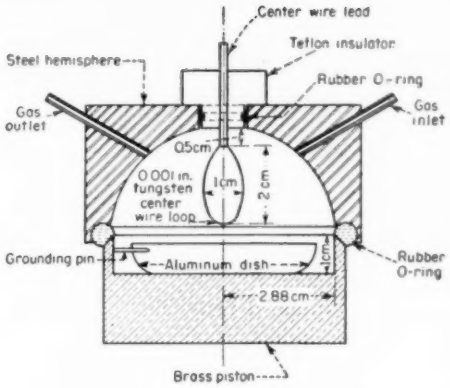

1 COUNTER CHAMBER, for easy decontamination, is lined with strippable coating of Al foil taken from paper capacitor. Foil was applied patchwise by wiping with cloth; paraffin film on foil caused it to adhere to wall while cloth wiped paraffin off exterior surface. Positive grounding of metal sample dish, to provide reproducible counting rates, is achieved by impaling dish on brass pin. Wire loop is changed by replacing center wire lead with hollow steel tube (hypodermic needle) through which ends of loop are threaded; loop is held in tube by inserting brass pin into top to wedge loop ends against tube

Evaluating the Performance of the Internal Counter

Good geometry and sensitivity to low-level, low-energy radiation recommend the internal proportional counter for assaying alpha and beta activity. The efficiency of a modified counter was studied for several beta emitters

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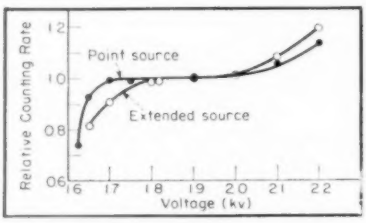
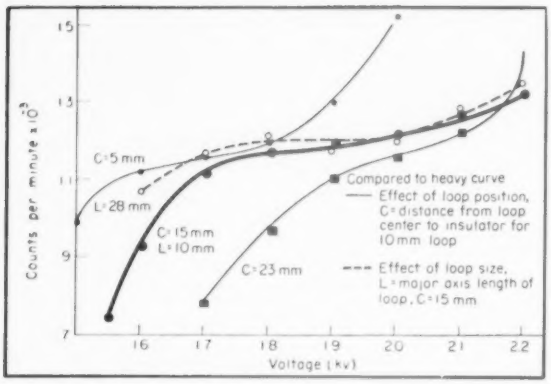


2 VOLTAGE PLATEAU must be determined with extended source having same area as sample to be counted for reproducible and accurate counting. Curves were obtained using 1-mm-diameter point source and 48-mm-diameter extended source

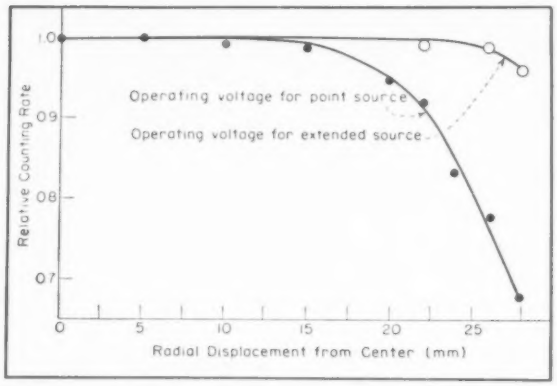
THE LOW RESOLUTION LOSS and high sensitivity of the internal gas-flow proportional counter (*1–3*) make it applicable to counting both high and low levels of alpha and beta radioactivity. To convert the observed counting rates to absolute radioactivity (curies), geometry, backscatter (*4*), self-absorption, and absorption (*5*) must be evaluated.

The internal counter selected for these studies accepts relatively large planchets (50-mm diameter), permitting minimum self-absorption in large samples. The counting system consists of the counting chamber, preamplifier, scaler, timer, and register and the argon-methane counting gas. For optimum counter performance, it was necessary to (1) determine the voltage plateau (*6*) with an extended source, (2) line the chamber with a metal foil that could be replaced when accidentally contaminated, and (3) assure effi-

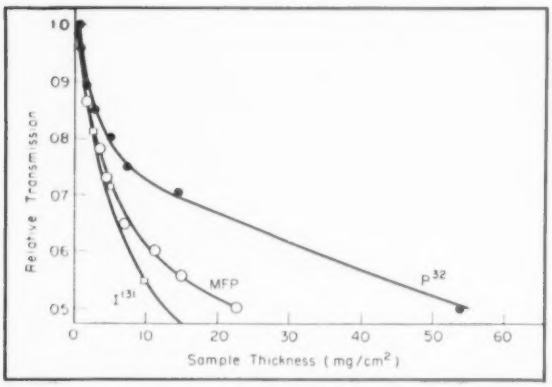
* PRESENT ADDRESS: Mound Laboratory (Monsanto Chemical Co., contractor) Miamisburg, Ohio.


Counts per minute x 10³
Voltage (kv)
C=5 mm
L=28 mm
C=15 mm
L=10 mm
C=23 mm
Compared to heavy curve
Effect of loop position, C=distance from loop center to insulator for 10 mm loop
Effect of loop size, L=major axis length of loop, C=15 mm

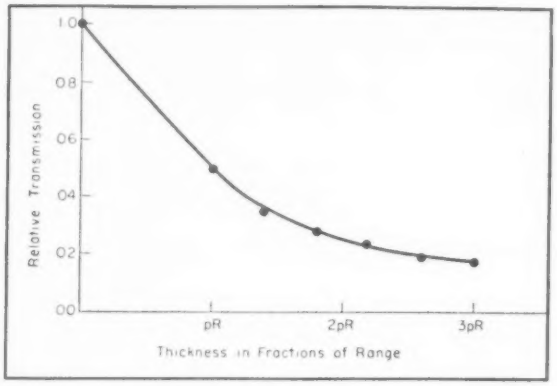
3 SIZE AND POSITION OF LOOP affect the voltage plateau. Best plateau occurs when loop is centered in hemisphere (its center 15 mm from insulator). When centered, loop size has small effect on length and slope of plateau; 20–28 mm loops give longer and flatter plateaus. Loops larger than 28 mm cause high-voltage discharges to ground; loop having 20-mm major axis was selected since it is more rigid. Loop must be replaced when it gives poor plateau characteristics, caused by contamination, physical distortion, or pitting of the wire


Relative Counting Rate
Operating voltage for point source
Operating voltage for extended source
Radial Displacement from Center (mm)

4 GEOMETRY is 50% for both point source (8) and extended source; this may be reduced by poor detection at periphery of chamber. Detection efficiency for point source displaced at right angles to plane of wire loop was investigated with 1-mm-diameter P^{32} source. Operating voltages were selected at 75 volts above threshold of point-source plateau and from middle of extended-source plateau. In latter case, efficiency is constant for sources up to 50-mm diameter



5 BETA SELF-ABSORPTION (9) was determined on stock suspensions of I^{131}, P^{32}, and 1-yr-old mixed fission products. Samples were transferred in triplicate to tared counting dishes (48-mm diameter), brought to volume with suspension fluid, and evaporated to dryness. Dishes were reweighed and counted over two equal periods. For I^{131} and mixed fission products, data (cpm/mg) were plotted and extrapolated to zero sample thickness. For P^{32}, value at zero thickness was determined by calculation based on assay of added P^{32} activity and known weight of precipitate that contained this activity. Results are similar to those obtained by Graf *et al.* (2) for Ca^{45}



6 ALPHA SELF-ABSORPTION curve is calculated from $S = a(1 - t/2pR)$, modified for 2π geometry from a derivation by Hull (10); S = transmitted alpha particles per min per mg of sample, a = emitted alpha particles/min/mg, t = thickness of sample, p = maximum fraction of range that particles can spend in sample and still be counted, and R = alpha particle range in sample. At sample thickness greater than pR, $S = 0.5aR/t$. Range of alpha particles in substances other than air can be estimated from (11) $R = 3.2 \times 10^{-4}(R_a A^{1/3}/\rho)$, where R_a = range in air (cm), ρ = density of absorber, and A = average atomic weight of absorber

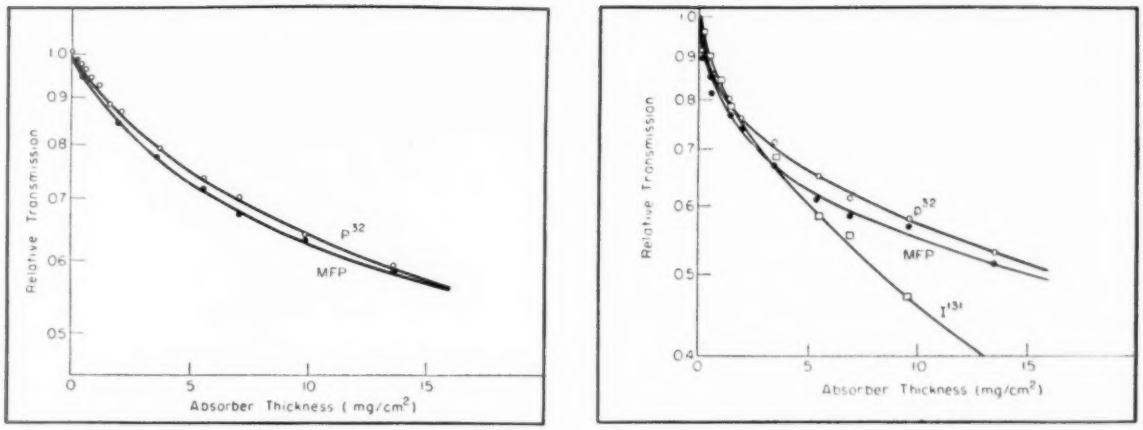
cient counting by grounding the sample and centrally locating a wire loop of proper size within the chamber.

The counting efficiency may be expressed as $\xi = Y/D = GBT$ where Y = observed radioactivity, D = absolute activity, G = geometry factor, B = backscatter factor, and T = transmission factor (correction for self-absorption).

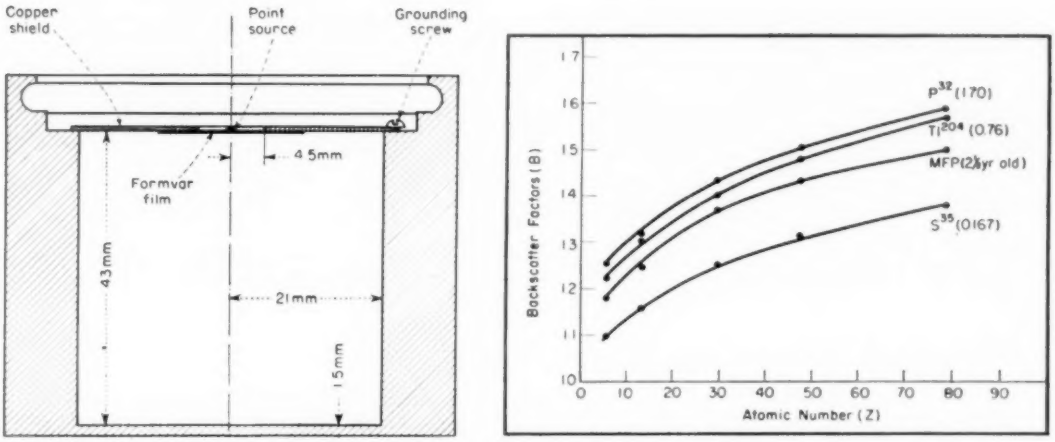
For the internal counter, $G = 0.50$. Since B and T are energy dependent (7), the counting efficiency is a function of the radiation energy. If self-absorption is made negligible by using very thin samples, $T = 1.00$. Thus $\xi = 0.50B$. For beta emitters, since $1 < B < 2$ then $0.50 < \xi < 1.00$; for alpha emitters, $1.00 < B < 1.04$ and consequently $0.50 < \xi < 0.52$.

The background of the internal counter is 45–55 cpm for beta and 0.1–0.5 cpm for alpha radiation. For low levels of radioactivity, less than background values, the statistical counting error becomes large for a practical counting period of about ½ hr. Assuming a minimum detectable activity equal to the counting error at the 95% confidence level, the minimum detectable activity for the counter is 0.31 $\mu\mu c$ for alpha activity and 1.6–3.2 $\mu\mu c$ for beta activity, depending on the energy.

In the preparation of samples for beta self-absorption measurements, I^{131}



7 TRANSMISSION THROUGH AL ABSORBERS was determined for collimated (left) and uncollimated (right) β-rays. Lead collimater 3.2 mm thick having central hole 3.2 mm in diameter was placed above sample; 0–15 mg/cm² Al absorbers were 3.2 mm above sample. For uncollimated radiation, first absorber (0.125 mg/cm²) was placed on sample and served as cover to prevent contamination of subsequent absorbers; absorbers were grounded to obtain unsuppressed count. Marked decrease in transmission for uncollimated radiation over that of collimated radiation is due to oblique path taken by much of radiation in passing through absorbers



8 BACKSCATTER FACTORS for beta emitters were determined with deep-well piston together with same hemisphere; amount of backscatter counted is negligible with well at least 15 mm deep. Copper sourceholder (0.020 in. thick), grounded and held in place by screw, is effective in absorbing all backscattered radiation of P^{32}. Hole in shield is large enough to give 2π geometry for 1-mm-diameter source. Source is dried on double layer of Formvar film (12), since pin holes of single layer give poor plateau characteristics for S^{35}; film is then sprayed with solution of Anstac M (Chemical Development Corp., Danvers, Mass.) to prevent build-up of electrostatic charge. Thus mounted, 2π activity is determined with negligible backscatter; with absorber taped under source, activity is determined with backscatter. Ratio of count with backscatter to that without backscatter is the backscatter factor

(iodide) was diluted with stable iodide, precipitated with lead acetate as lead iodide, washed, suspended in methyl alcohol, distributed in counting dishes, and dried at 50° C. Phosphorus-32 (phosphate) was diluted with trisodium phosphate, precipitated as $MgNH_4PO_4 \cdot 6H_2O$, washed, suspended in methyl alcohol, and air dried. Mixed fission products were diluted with nitrates of cerium and strontium, precipitated with ammonium carbonate, washed, suspended in distilled water, and dried at room temperature.

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Developments in Internal Dose Determinations

A clear picture of the basis for values in the Internal Dose Handbook of maximum permissible concentrations of radioisotopes for chronic exposure is complemented in this article by newly derived MPC values for single exposures and for body excretion with either chronic or single exposure

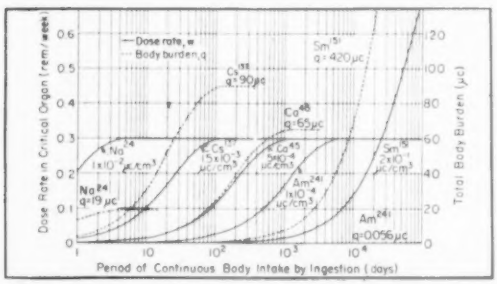
Dose rate, w
Body burden, q
Dose Rate in Critical Organ (rem/week)
Total Body Burden (μc)
Period of Continuous Body Intake by Ingestion (days)

FIG. 1. Relation of dose rate to body burden for continuous intake by ingestion

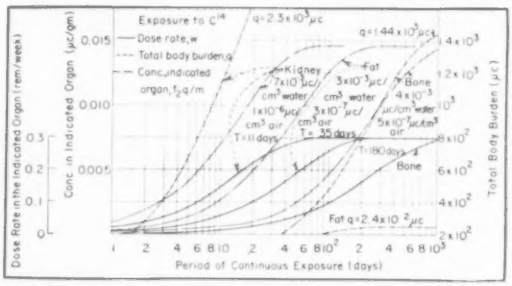
Exposure to C14
Dose rate, w
Total body burden, q
Conc. in indicated organ, f2q/m
Dose Rate in the Indicated Organ (rem/week)
Conc. in Indicated Organ (μc/gm)
Total Body Burden (μc)
Period of Continuous Exposure (days)

FIG. 2. Build-up of total body burden of carbon-14, increase in concentration and in average dose rate in organ. At 6.65 half-lives in each case, 99% equilibrium is reached. C^{14} is assumed consumed in soluble form

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THREE FUNCTIONS are served by this article: First, it clarifies the choice of values for maximum permissible concentrations (MPC) of a radioisotope for chronic exposure. Second, it provides the basis of calculation of the MPC for single exposure. Third, it gives the basis for recalculation of certain MPC based on the gastro-intestinal tract for continuous exposure.

In the discussion on chronic exposure in the first section of this article, the rem unit is defined as used in publications prior to the summer of 1953, i.e., 1 rem = 1 rep/RBE. The following sections do not relate to previous publications and use the new definition of the rem, i.e., 1 rem = 1 rad in tissue/RBE.

Maximum permissible concentration of a radioisotope for chronic exposure leading to a maximum permissible body burden under equilibrium conditions

Several reports (*1–7*) have been prepared that give the recommended maximum permissible body burden and maximum permissible concentration in air and water of radioisotopes under equilibrium conditions. In obtaining these values it was assumed that an equilibrium condition is reached if a radioisotope is taken into the body continuously over a period of time that is long compared to the effective half-life of the radioisotope in the critical organ. The critical organ is defined as that organ of the body receiving the radioisotope that results in the greatest damage to the body. When equilibrium is reached the amount of the radioisotope going into the critical body organ is equal to that lost from the body by biological elimination and by radioactive decay per unit time. Under these conditions the maximum permissible total body burden, q, is such that the amount in the critical body organ delivers to it an average dose of 0.3 rem/wk, as illustrated by the curves in Fig. 1.

In this simplified method of calculation of the maximum permissible burden of a radioisotope, it is assumed that the radioactive material is uniformly distributed in the critical organ. However, this is rarely, if ever, the case. Usually the radioisotope is localized in so-called "hot spots" within the organ so that some of the tissue may receive a dose of much more than 0.3 rem/wk while other tissue receives correspondingly less. The simplifying assumption is tolerated because: (1) there are insufficient biological data available in most cases to warrant additional re-

*ORNL is operated for the Atomic Energy Commission by Carbide and Carbon Chemicals Co.

Maximum Permissible Values of Intake and Fecal Excretion for a Single Exposure and Total Excretion Rate for Continuous Exposure

Z	Radioisotope	Critical organ	Amount ingested ($\mu c/cm^3$) in a single day to deliver a dose to the critical organ of: ‡ 0.043 rem/1 day	0.3 rem/1 wk	15.7 rem/1 yr	Amount inhaled ($\mu c/cm^3$) in a single day to deliver a dose to the critical organ of: ‡ 0.043 rem/1 day	0.3 rem/1 wk	15.7 rem/1 yr	Maximum permissible excretion: Fecal, 1st few days after single intake (μc)	Maximum permissible excretion: Total, equilibrium, after continuous exposure ($\mu c/day$)
1	H^3	T. Body	5	5	60	7×10^{-4}	7×10^{-4}	9×10^{-3}		4×10^{2}
		Lungs				6×10^{-5}	6×10^{-5}	10^{-4}	trace	
		GI*	5	5	60	7×10^{-4}	7×10^{-4}	9×10^{-3}	trace	
4	Be^7	Bone	90	90	4×10^{2}	4×10^{-4}	4×10^{-4}	2×10^{-3}		4
		Lungs				9×10^{-6}	10^{-5}	6×10^{-5}	10^{2}	
		GI	2×10^{-2}	0.1	6	3×10^{-6}	2×10^{-5}	10^{-3}	3×10^{2}	
6	C^{14} (CO_2)	Fat	0.1	0.2	1	2×10^{-5}	2×10^{-5}	2×10^{-4}		0.7
		Bone	1	1	2	2×10^{-4}	2×10^{-4}	3×10^{-4}		
		Lungs				6×10^{-6}	6×10^{-6}	2×10^{-5}	4	
		GI	6×10^{-2}	0.4	20	10^{-5}	7×10^{-5}	4×10^{-3}	3×10^{2}	
9	F^{18}	Bone	1	7	4×10^{2}	10^{-4}	10^{-3}	5×10^{-2}		2
		Lungs				10^{-5}	9×10^{-5}	5×10^{-3}	trace	
		GI*	>1	>7	$>4\times10^{2}$	$>10^{-4}$	$>10^{-3}$	$>5\times10^{-2}$	trace	
11	Na^{24}	T. Body	2×10^{-2}	8×10^{-2}	4	2×10^{-6}	10^{-5}	6×10^{-4}		0.8
		Lungs				2×10^{-7}	10^{-6}	5×10^{-5}	0.6	
		GI	8×10^{-3}	6×10^{-2}	3	10^{-6}	10^{-5}	5×10^{-4}	6	
15	P^{32}	Bone	2×10^{-2}	2×10^{-2}	0.4	2×10^{-6}	3×10^{-6}	4×10^{-5}		0.5
		Lungs				5×10^{-7}	6×10^{-7}	10^{-5}	2	
		GI	8×10^{-4}	6×10^{-3}	0.3	10^{-7}	10^{-6}	5×10^{-5}	40	
16	S^{35}	Skin	0.2	0.2	2	2×10^{-5}	2×10^{-5}	3×10^{-4}		0.6†
		Lungs				6×10^{-6}	6×10^{-6}	3×10^{-5}	40	
		GI	6×10^{-3}	4×10^{-2}	2	10^{-6}	8×10^{-6}	4×10^{-4}	40	
17	Cl^{36}	T. Body	0.1	0.1	0.9	2×10^{-5}	2×10^{-5}	10^{-4}		5
		Lungs				10^{-6}	10^{-6}	3×10^{-6}	8	
		GI	10^{-2}	8×10^{-2}	4	2×10^{-6}	10^{-5}	8×10^{-4}	9	
19	K^{42}	Muscle	2×10^{-2}	0.1	5	3×10^{-6}	10^{-5}	7×10^{-4}		0.2
		Lungs				4×10^{-7}	2×10^{-6}	10^{-4}	2	
		GI	3×10^{-3}	2×10^{-2}	1	6×10^{-7}	4×10^{-6}	2×10^{-4}	5	
20	Ca^{45}	Bone	0.1	0.1	0.3	8×10^{-6}	9×10^{-6}	2×10^{-5}		3×10^{-3}
		Lungs				4×10^{-6}	4×10^{-6}	2×10^{-5}	5	
		GI	2×10^{-2}	0.1	7	3×10^{-6}	2×10^{-5}	10^{-3}	30	

finements; (2) the total body damage and/or the maximum permissible exposure rate of 0.3 rem/wk can be more closely related to the average dose rate in a critical body organ than the maximum dose rate in some small portion of tissue within the organ; and (3) the "hot spots" may migrate within the organ.

The equations used (*5*) for determining the maximum permissible body burden, q, and the maximum permissible concentration (MPC) of a radioisotope in water and air under equilibrium conditions are

$$q = \frac{2.6 \times 10^{-3} mW}{f_2 \Sigma(\mathrm{RBE})E} = \frac{(\mathrm{MPC})Tf(1 - e^{-0.693\, t/T})}{3af_2} \quad (1)$$

where q (μc) accumulated in the total body after time t (days) delivers a dose rate W (rem/wk = RBE × rep/wk) to critical body organ of mass m (gm). A fraction, f, of the activity taken into the body by ingestion or inhalation arrives in the critical body organ where it is eliminated with an effective half-life, T (days), and the fraction in the critical organ of that in the total body is f_2. Each disintegration of the radioisotope has a relative biological effectiveness, RBE, and results in an average energy dissipation in the tissue of E (Mev). The constant $a = 10^{-4}$ and 10^{-8} is for water and air, respectively.

The solid curves in Fig. 1 are plots of Eq. 1 in which the average dose rate, W, is a function of exposure time, t. They indicate that radioisotopes with short effective half-lives such as Na^{24} ($T = 0.61$ days) reach equilibrium in a few days; but in cases such as Sm^{151} in which T is large ($T = 3.9 \times 10^4$ days), 99% equilibrium is not reached until 710 years. For practical purposes none of the exposure periods are assumed to be greater than a life span of 70 years. Of the radioisotopes considered in the Internal Dose Handbook (*5*), all reach equilibrium in a period less than 70 years except Pu^{239}, Sm^{151}, Ra^{226} and natural Th. Radioisotope Sr^{90}, with the next longest effective half-life, reaches 99% equilibrium in 49 years.

The dashed lines in Fig. 1 are plots of Eq. 1 in which the total body burden, q, is plotted as a function of exposure time, t. A comparison of the dashed curves with the solid curves emphasizes that, whereas all the curves reach the same dose rate of 0.3 rem/wk at equilibrium, there may be considerable variation of the maximum permissible total body burden, q, or of the maximum permissible burden in the critical organ, $f_2 q$.

Figure 2 is a plot of values obtained from Eq. 1 in which the dose rate to the critical organ, W, the total body burden, q, and the concentration in the critical organ, $q f_2/m$, are plotted as a function of time of exposure, t. These three curves are plotted for the conditions in which each of three body or-

Maximum Permissible Values (continued)

			Ingested			Inhaled				
Z	Radio-isotope	Critical organ	0.043 rem/ 1 day	0.3 rem/ 1 wk	15.7 rem/ 1 yr	0.043 rem/ 1 day	0.3 rem/ 1 wk	15.7 rem/ 1 yr	Single (μc)	Continuous (μc/day)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
21	Sc^{46}	Liver	6	6	10^2	10^{-6}	10^{-6}	2×10^{-5}		0.1
		Spleen	8	9	10^2	2×10^{-6}	2×10^{-6}	3×10^{-5}		
		Lungs				3×10^{-7}	3×10^{-7}	10^{-6}	3	
		GI	4×10^{-4}	3×10^{-3}	0.1	7×10^{-5}	5×10^{-7}	2×10^{-5}	5	
21	Sc^{47}	Liver	10	30	10^3	3×10^{-6}	6×10^{-6}	3×10^{-4}		0.2
		Spleen	20	40	2×10^3	5×10^{-6}	8×10^{-6}	4×10^{-4}		
		Lungs				2×10^{-6}	3×10^{-6}	10^{-4}	40	
		GI	9×10^{-4}	6×10^{-3}	0.3	2×10^{-7}	10^{-6}	6×10^{-5}	10	
21	Sc^{48}	Liver	4	10	5×10^2	9×10^{-7}	2×10^{-6}	10^{-4}		6×10^{-2}
		Spleen	7	20	9×10^2	2×10^{-6}	4×10^{-6}	2×10^{-4}		
		Lungs				3×10^{-7}	6×10^{-7}	3×10^{-5}	8	
		GI	4×10^{-4}	3×10^{-3}	0.1	7×10^{-8}	5×10^{-7}	3×10^{-5}	6	
23	V^{48}	Bone	10	10	2×10^2	2×10^{-5}	3×10^{-5}	5×10^{-4}		0.3
		Lungs				2×10^{-7}	2×10^{-7}	3×10^{-6}	3	
		GI	3×10^{-4}	2×10^{-3}	0.1	5×10^{-8}	4×10^{-7}	2×10^{-5}	5	
24	Cr^{51}	Kidneys	20	30	3×10^2	5×10^{-4}	5×10^{-4}	5×10^{-3}		20
		Lungs				3×10^{-5}	3×10^{-5}	4×10^{-4}	4×10^2	
		GI	2×10^{-2}	0.2	9	4×10^{-6}	3×10^{-5}	2×10^{-3}	3×10^2	
25	Mn^{56}	Kidneys	0.2	1	60	3×10^{-6}	2×10^{-4}	10^{-2}		7×10^{-2}
		Liver	0.4	2	10^2	5×10^{-6}	3×10^{-5}	2×10^{-3}		
		Lungs				10^{-6}	8×10^{-6}	4×10^{-4}	90	
		GI	3×10^{-3}	2×10^{-2}	1	5×10^{-7}	4×10^{-6}	2×10^{-4}	40	
26	Fe^{55}	Blood	0.4	0.4	2	6×10^{-5}	6×10^{-5}	2×10^{-4}		7†
		Lungs				6×10^{-5}	6×10^{-5}	10^{-4}	10^2	
		GI	0.1	0.9	50	2×10^{-5}	2×10^{-4}	8×10^{-3}	2×10^2	
26	Fe^{59}	Blood	5×10^{-3}	5×10^{-3}	4×10^{-2}	7×10^{-7}	7×10^{-7}	6×10^{-6}		7×10^{-2}†
		Lungs				4×10^{-7}	4×10^{-7}	3×10^{-6}	1	
		GI	3×10^{-3}	2×10^{-2}	1	5×10^{-7}	3×10^{-6}	2×10^{-4}	2	
27	Co^{60}	Liver	0.2	0.3	7	10^{-5}	2×10^{-5}	4×10^{-4}		0.1
		Spleen	2	3	70	2×10^{-4}	2×10^{-4}	4×10^{-3}		
		Lungs				2×10^{-7}	2×10^{-7}	6×10^{-7}	2	
		GI	4×10^{-4}	3×10^{-3}	0.2	8×10^{-8}	5×10^{-7}	3×10^{-5}	5	
28	Ni^{59}	Liver	3	4	10^2	2×10^{-4}	3×10^{-4}	6×10^{-3}		2†
		Lungs				7×10^{-6}	7×10^{-6}	2×10^{-5}	70	
		GI	4×10^{-3}	3×10^{-2}	1	7×10^{-7}	5×10^{-6}	2×10^{-4}	50	

gans—kidney, fat, and bone—is assumed to be the critical body organ for C^{14}. There is considerable variation in the equilibrium value of the total body burden, q, and in the corresponding MPC value as seen from the graph for each family of curves. In most cases the organ that results in the smallest equilibrium value of q or smallest MPC by this method of calculation is taken as the critical organ (in the case illustrated in Fig. 2 the fat is the critical organ) because the selection of any other organ is equivalent to permitting a dose rate in excess of 0.3 rem/wk to some of the body organs after equilibrium is reached. As is the case here, it is frequently necessary in the practice of health physics to make calculations based on several body organs. The body organ accumulating the maximum dose usually is the critical organ and is the one for which the following expression is a maximum

$$EfT(1 - e^{-0.693t/T})/mT, \qquad (2)$$

where T_r is the radioactive half-life and the other terms are the same as in Eq. 1. As would be expected, all the dose rate curves in Fig. 2 reach a constant value at 0.3 rem/wk, and all the curves for the concentration in body organs reach a saturation value of $7.8 \times 10^{-4}/(\text{RBE})E$. In the case of gamma-emitting radioisotopes this saturation value is different for each body organ since the absorption of the energy of the gamma ray in the body organ is a function of the effective radius of the organ. However, since C^{14} does not give off gamma radiation, all the concentration curves in Fig. 2 saturate at the same value. It should be noted from Fig. 2 that the effective half-life, T, does not affect the magnitude of the saturation values but rather the time at which saturation is reached.

With fat chosen as the critical organ for C^{14} from Fig. 2, the curves for the dose rate and body burden in the various body organs can be plotted as a function of time for a fixed concentration of C^{14} in air and/or water. This has been done for a concentration of 3×10^{-3} μc of C^{14} in 1 cm^3 water in Fig. 3 and, since the fat has the greatest concentration, only the fat receives an exposure of 0.3 rem/wk under equilibrium conditions. When the total body burden, q, has reached equilibrium, the fraction of the radioisotope in the critical organ, f_2, is given by the ratio of the ordinates, i.e., $f_2 = q_2/q$.

As explained in previous publications (5, 7) biological elimination of radioactive material from the body does not follow as simple a pattern as implied by Eq. 1. Nevertheless, in most cases this method of determining the maximum permissible concentration in air and water is satisfactory. More refinement in the method of calculating these values will hardly be justified until more detailed biological information and data of greater accuracy are available.

29	Cu^{64}	Liver	9×10^{-2}	0.4	20	7×10^{-6}	3×10^{-5}	2×10^{-3}		0.1†
		Lungs				3×10^{-6}	10^{-5}	8×10^{-4}	10^{2}	
		GI	5×10^{-3}	4×10^{-2}	2	9×10^{-7}	6×10^{-6}	3×10^{-4}	60	
30	Zn^{65}	Bone	2	2	30	8×10^{-5}	9×10^{-5}	9×10^{-4}		2†
		Lungs				10^{-6}	10^{-6}	3×10^{-6}	10	
		GI	2×10^{-3}	10^{-2}	0.7	4×10^{-7}	2×10^{-6}	10^{-4}	30	
31	Ga^{72}	Bone	10	70	4×10^{3}	6×10^{-6}	3×10^{-5}	2×10^{-3}		0.6
		Lungs				3×10^{-7}	10^{-6}	7×10^{-5}	20	
		GI	5×10^{-4}	4×10^{-3}	0.2	10^{-7}	7×10^{-7}	4×10^{-5}	8	
32	Ge^{71}	Kidneys	60	10^{2}	4×10^{3}	3×10^{-4}	4×10^{-4}	2×10^{-2}		20
		Lungs				3×10^{-5}	4×10^{-5}	9×10^{-4}	5×10^{2}	
		GI	2×10^{-2}	0.1	6	3×10^{-6}	2×10^{-5}	10^{-3}	2×10^{2}	
33	As^{76}	Kidneys	0.5	2	80	6×10^{-6}	2×10^{-5}	10^{-3}		2×10^{2}
		Lungs				3×10^{-7}	10^{-6}	6×10^{-5}	10	
		GI	2×10^{-4}	2×10^{-3}	9×10^{2}	4×10^{-8}	3×10^{-7}	2×10^{-5}	4	
37	Rb^{86}	Muscle	4×10^{-2}	5×10^{-2}	1	5×10^{-6}	7×10^{-6}	2×10^{-4}		3
		Lungs				5×10^{-7}	5×10^{-7}	7×10^{-6}	trace	
		GI*	$>4\times10^{-2}$	$>5\times10^{-2}$	>1	$>5\times10^{-6}$	$>7\times10^{-6}$	$>2\times10^{-4}$	trace	
38	Sr^{89}	Bone	2×10^{-2}	2×10^{-2}	0.1	2×10^{-6}	3×10^{-6}	10^{-5}		7×10^{-3}
		Lungs				6×10^{-7}	6×10^{-7}	4×10^{-6}	3	
		GI	7×10^{-4}	5×10^{-3}	0.3	10^{-7}	9×10^{-7}	5×10^{-5}	4	
38	Sr^{90} + Y^{90}	Bone	10^{-2}	10^{-2}	10^{-2}	10^{-6}	10^{-6}	10^{-6}		4×10^{-3}
		Lungs				3×10^{-7}	3×10^{-7}	8×10^{-7}	2	
		GI	4×10^{-4}	3×10^{-3}	0.1	7×10^{-8}	5×10^{-7}	2×10^{-5}	2	
39	Y^{91}	Bone	20	20	80	4×10^{-6}	4×10^{-6}	2×10^{-5}		2×10^{-2}
		Lungs				6×10^{-7}	6×10^{-7}	4×10^{-6}	8	
		GI	3×10^{-4}	2×10^{-3}	0.1	5×10^{-8}	3×10^{-7}	2×10^{-5}	4	
41	Nb^{95}	Bone	0.1	0.1	2	2×10^{-5}	2×10^{-5}	2×10^{-4}		0.8
		Lungs				7×10^{-7}	7×10^{-7}	6×10^{-6}	5	
		GI	2×10^{-3}	10^{-2}	0.7	3×10^{-7}	2×10^{-6}	10^{-4}	20	
42	Mo^{99}	Bone	70	10^{2}	5×10^{3}	8×10^{-3}	2×10^{-2}	0.7		0.1†
		Lungs				7×10^{-7}	10^{-6}	6×10^{-5}	5	
		GI	3×10^{-3}	2×10^{-2}	1	5×10^{-7}	4×10^{-6}	2×10^{-4}	10	
43	Tc^{98}	Kidneys	0.1	0.2	10	10^{-5}	3×10^{-5}	10^{-3}		3
		Lungs				2×10^{-7}	4×10^{-7}	10^{-5}	2	
		GI	10^{-3}	7×10^{-3}	0.4	2×10^{-7}	10^{-6}	6×10^{-5}	7	
44	Ru^{106} + Rh^{106}	Kidneys	4	5	50	9×10^{-7}	10^{-6}	10^{-5}		3×10^{-2}
		Lungs				2×10^{-7}	2×10^{-7}	7×10^{-7}	3	
		GI	10^{-4}	8×10^{-4}	1×10^{2}	2×10^{-8}	10^{-7}	7×10^{-6}	2	
45	Rh^{105}	Kidneys	0.1	0.3	10	5×10^{-6}	10^{-5}	6×10^{-4}		0.3
		Lungs				9×10^{-7}	2×10^{-6}	10^{-4}	20	
		GI	10^{-3}	7×10^{-3}	0.4	2×10^{-7}	10^{-6}	6×10^{-5}	10	
46	Pd^{103} + Rh^{103}	Kidneys	8×10^{-2}	0.1	4	5×10^{-6}	8×10^{-6}	3×10^{-4}		0.8
		Lungs				5×10^{-6}	5×10^{-6}	8×10^{-5}	50	
		GI	5×10^{-3}	3×10^{-2}	2	9×10^{-7}	6×10^{-6}	3×10^{-4}	60	

Dose rate, w
Body burden, Σq
w in fat
q_2 μc in fat
w in bone
w in kidney
q_1 μc in bone
q_3 μc in kidney
q_1 μc in total body
Dose Rate, w (rem/week)
Burden, Σq_i in Body Organ (μc)
Period of Continuous Body Intake (days)

FIG. 3. Build-up and distribution of C^{14} in the body and resulting dose when C^{14} is ingested continuously in concentration of 3×10^{-3} μc/cm³ of water

Per Cent Ingested Radioisotope in Critical Organ
Time Following a Single Ingestion of a Radioisotope (days)
Average Dose Rate in the Critical Body Organ (rem/day)

FIG. 4. Per cent of ingested radioisotope and dose rate after single ingestion

Sometimes chronic exposure data such as that plotted in Figs. 1, 2 and 3 are available, but usually the best one can do is to try to extrapolate from single dose experiments such as the one illustrated in Fig. 4. Retention in the critical organ may have a sharp maximum (solid curve) or a broad maximum (dashed curve). The initial shape of the curve depends upon the radioisotope, its chemical form, and the method of body intake. For the method of Eq. 1 to be applicable, one should find data giving the per cent retention in the critical body organ over a long period of time—including a long straight portion *bcd* of the curve—or an approximation to this straight line such as *bgd*. If the data are not cor-

Maximum Permissible Values (continued)

Z	Radioisotope	Critical organ	Ingested: 0.043 rem/1 day	Ingested: 0.3 rem/1 wk	Ingested: 15.7 rem/1 yr	Inhaled: 0.043 rem/1 day	Inhaled: 0.3 rem/1 wk	Inhaled: 15.7 rem/1 yr	Single (μc)	Continuous (μc/day)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
47	Ag^{105}	Liver	8	20	7×10^{2}	7×10^{-5}	10^{-4}	5×10^{-3}	5	
		Lungs				2×10^{-7}	2×10^{-7}	2×10^{-6}		
		GI	4×10^{-4}	3×10^{-3}	0.1	7×10^{-8}	5×10^{-7}	3×10^{-5}	3	
47	Ag^{111}	Liver	20	40	2×10^{3}	10^{-4}	3×10^{-4}	10^{-2}	6	
		Lungs				10^{-6}	10^{-6}	3×10^{-6}		10
		GI	5×10^{-4}	3×10^{-3}	0.2	8×10^{-8}	6×10^{-7}	3×10^{-5}	7	
48	Cd^{109}+ Ag^{109m}	Liver	9	9	30	9×10^{-6}	10^{-5}	3×10^{-5}		0.1
		Lungs				5×10^{-6}	5×10^{-6}	10^{-5}	0.5	
		GI	0.7	5	2×10^{2}	10^{-4}	8×10^{-4}	4×10^{-2}	80	
50	Sn^{113}	Bone	10	10	70	4×10^{-6}	5×10^{-5}	3×10^{-4}	20	0.8
		Lungs				10^{-6}	10^{-6}	5×10^{-6}		
		GI	2×10^{-3}	10^{-2}	0.6	3×10^{-7}	2×10^{-6}	10^{-4}	10	
52	Te^{127}	Kidneys	0.6	0.7	10	2×10^{-6}	3×10^{-6}	4×10^{-5}	30	0.1
		Lungs				10^{-6}	10^{-6}	5×10^{-6}		
		GI	7×10^{-4}	5×10^{-3}	0.3	10^{-7}	9×10^{-7}	5×10^{-5}	10	
52	Te^{129}	Kidneys	0.2	0.2	5	7×10^{-7}	9×10^{-7}	2×10^{-5}	8	
		Lungs				2×10^{-7}	3×10^{-7}	2×10^{-6}	2	4×10^{-2}
		GI	2×10^{-4}	2×10^{-3}	9×10^{-2}	4×10^{-8}	3×10^{-7}	2×10^{-5}	3	
53	I^{131}	Thyroid	2×10^{-4}	2×10^{-4}	6×10^{-3}	3×10^{-8}	3×10^{-8}	8×10^{-7}		10^{-3}
		Lungs				8×10^{-7}	10^{-6}	3×10^{-5}	trace	
		GI*	$>2\times10^{-4}$	$>2\times10^{-4}$	$>6\times10^{-3}$	$>3\times10^{-8}$	$>3\times10^{-8}$	$>8\times10^{-7}$	trace	
55	Cs^{137}+ Ba^{137m}	Muscle	4×10^{-2}	5×10^{-2}	0.6	6×10^{-6}	7×10^{-6}	9×10^{-5}	2	
		Lungs				6×10^{-7}	6×10^{-7}	10^{-6}		
		GI*	$>4\times10^{-2}$	$>5\times10^{-2}$	>0.6	$>6\times10^{-6}$	$>7\times10^{-6}$	$>9\times10^{-5}$	trace	
56	Ba^{140}+ La^{140}	Bone	4×10^{-2}	4×10^{-2}	0.8	10^{-6}	2×10^{-6}	3×10^{-5}		3×10^{-2}
		Lungs				2×10^{-7}	2×10^{-7}	4×10^{-6}	2	
		GI	2×10^{-4}	10^{-3}	6×10^{-2}	3×10^{-8}	2×10^{-7}	10^{-5}	2	
57	La^{140}	Bone	4	9	5×10^{2}	5×10^{-6}	10^{-5}	6×10^{-4}		0.6
		Lungs				3×10^{-7}	7×10^{-7}	3×10^{-5}	9	
		GI	3×10^{-3}	2×10^{-3}	0.1	5×10^{-8}	4×10^{-7}	2×10^{-5}	5	
58	Ce^{144}+ Pr^{144}	Bone	10	10	20	2×10^{-6}	2×10^{-6}	4×10^{-6}		10^{-2}
		Lungs				2×10^{-7}	2×10^{-7}	8×10^{-7}	3	
		GI	10^{-3}	8×10^{-4}	4×10^{-2}	2×10^{-5}	10^{-7}	8×10^{-6}	2	
59	Pr^{142}	Bone	7	8	2×10^{2}	2×10^{-5}	2×10^{-5}	3×10^{-4}		5×10^{-2}
		Lungs				10^{-6}	10^{-6}	2×10^{-5}	20	
		GI	5×10^{-4}	4×10^{-3}	0.2	9×10^{-8}	6×10^{-7}	3×10^{-5}	8	

rected for decay before plotting, the effective half-life, T, is found from

$$d = be^{-0.693t/T} \qquad (3)$$

in which b and d are ordinates on the straight portion of the curve in Fig. 4, and t is the time interval between b and d. If line db is projected (dotted line in Fig. 4) back to the axis ($t = 0$), this intercept is the value for f in Eq. 1, the fraction initially deposited in the critical organ. Actually, f has no physical significance and has meaning only from the standpoint of its use in Eq. 1. It may be greater or less than the peak of the experimental curve, as illustrated in Fig. 4, and the area under curve *fbcd* may be either greater or less than that under the experimental curve. For lack of more accurate information, however, it is usually assumed that the area under this curve is equal to that under the experimental curve and that it is proportional to the radiation dose delivered to the critical organ.

Maximum permissible intake of a radioisotope in a single exposure

Whereas values of maximum permissible body burden and maximum permissible concentration in air and water for the equilibrium condition have been given in the Internal Dose Handbook (*5*) for some 70 radioisotopes, no maximum permissible single-exposure values have been published by the National Committee on Radiation Protection. Therefore, the single-exposure values published here—in the table—do not have official status. However, many persons are working with radioactive materials under conditions in which an accident could lead to a single exposure; it would be convenient to have available tables of values that apply in such a case. It was with this in mind that an effort was made to determine and list in the table the maximum permissible single-exposure values for the radioisotopes considered in the Internal Dose Handbook (*5*).

In the event of a single intake of a radioisotope the dose delivered to the critical body organ is considered to be proportional to the area under curve *fbcd* illustrated in Fig. 4 and is given by

$$D = [(73.9\, f\, I_0 T \Sigma(\mathrm{RBE})E)/m](1 - e^{-0.693t/T}) \qquad (4)$$

where D = total dose of ionizing radiation to the critical organ (rem = RBE × rad)* delivered in time t (days), and I_0 = total amount (μc) of radioisotope taken into body by inhalation or ingestion in a single event (for purposes of calculation assumed to be over a period of not more than 1 day). The maximum permissible concentrations in water $(\mathrm{MPC})_w$ and air $(\mathrm{MPC})_a$ for consumption during a single day are

$$(\mathrm{MPC})_w = I_0/2{,}200 \qquad (5)$$

$$(\mathrm{MPC})_a = I_0/2 \times 10^7 \qquad (6)$$

* The rad unit used in this section corresponds to an absorbed dose of 100 ergs/gm of medium. The rep unit used in the previous section corresponds to an absorbed dose of 93 ergs/gm of tissue.

61	Pm^{147}	Bone	2×10^{2}	2×10^{2}	5×10^{2}	5×10^{-5}	5×10^{-5}	10^{-4}		2			
		Lungs				5×10^{-6}	5×10^{-6}	10^{-5}	60				
		GI	2×10^{3}	2×10^{3}	0.8	4×10^{-7}	3×10^{-6}	10^{-4}	40				
62	Sm^{151}	Bone	5×10^{3}	5×10^{3}	5×10^{3}	3×10^{-4}	3×10^{-4}	3×10^{-4}	2×10^{3}	50			
		Lungs				2×10^{-5}	2×10^{-5}	4×10^{-5}					
		GI	8×10^{-3}	5×10^{-2}	3	10^{-6}	9×10^{-6}	5×10^{-4}	10^{2}	4×10^{-2}			
63	Eu^{154}	Bone	40	40	50	9×10^{-6}	9×10^{-6}	10^{-5}					
		Lungs				4×10^{-7}	4×10^{-7}	10^{-6}	5				
		GI	4×10^{-4}	3×10^{-3}	0.2	8×10^{-8}	5×10^{-7}	3×10^{-5}	7				
67	Ho^{166}	Bone	60	2×10^{2}	9×10^{3}	9×10^{-6}	3×10^{-5}	10^{-3}		0.3			
		Lungs				7×10^{-7}	2×10^{-6}	10^{-4}	20				
		GI	5×10^{-4}	3×10^{-3}	0.2	8×10^{-8}	6×10^{-7}	3×10^{-5}	6				
69	Tm^{170}	Bone	20	20	10^{2}	5×10^{-6}	5×10^{-6}	2×10^{-5}		4×10^{-2}			
		Lungs				10^{-6}	10^{-6}	4×10^{-6}	10				
		GI	5×10^{-4}	3×10^{-3}	0.2	8×10^{-8}	6×10^{-7}	3×10^{-5}	7				
71	Lu^{177}	Bone	10^{2}	2×10^{2}	10^{4}	3×10^{-5}	5×10^{-5}	2×10^{-3}		8			
		Lungs				2×10^{-6}	3×10^{-6}	8×10^{-5}	40				
		GI	10^{-3}	8×10^{-3}	0.4	2×10^{-7}	10^{-6}	8×10^{-5}	20				
73	Ta^{182}	Liver	10	10	40	2×10^{-6}	2×10^{-6}	9×10^{-6}		3×10^{-2}			
		Lungs				4×10^{-7}	4×10^{-7}	2×10^{-6}	5				
		GI	5×10^{-4}	3×10^{-3}	0.2	9×10^{-8}	6×10^{-7}	3×10^{-5}	8				
74	W^{181}	Bone	1	10	70	5×10^{-5}	5×10^{-4}	2×10^{-3}		3†			
		Lungs				3×10^{-7}	3×10^{-7}	10^{-6}	4				
		GI	7×10^{-4}	5×10^{-3}	0.2	10^{-7}	8×10^{-7}	4×10^{-5}	9				
75	Re^{183}	Thyroid	0.1	0.6	30	10^{-5}	7×10^{-5}	4×10^{-3}		3			
		Skin	2	3	10^{2}	3×10^{-4}	4×10^{-4}	10^{-2}					
		Lungs				5×10^{-7}	5×10^{-7}	2×10^{-6}	3				
		GI	2×10^{-3}	10^{-2}	0.7	4×10^{-7}	3×10^{-6}	10^{-4}	20				
77	Ir^{190}	Kidneys	0.2	0.2	6	10^{-6}	10^{-5}	4×10^{-4}		1			
		Spleen	3	3	70	10^{-6}	2×10^{-5}	4×10^{-4}					
		Lungs				2×10^{-6}	2×10^{-6}	4×10^{-5}	20				
		GI	3×10^{-3}	2×10^{-2}	1	6×10^{-7}	4×10^{-6}	2×10^{-4}	40				
77	Ir^{192}	Kidneys	3×10^{-2}	3×10^{-2}	0.4	2×10^{-6}	2×10^{-6}	2×10^{-5}		0.2			
		Spleen	0.4	0.4	2	2×10^{-6}	2×10^{-6}	10^{-5}					
		Lungs				3×10^{-7}	4×10^{-7}	2×10^{-6}	4				
		GI	5×10^{-4}	3×10^{-3}	0.2	9×10^{-8}	6×10^{-7}	3×10^{-5}	6				
78	Pt^{191}	Kidneys	3×10^{-2}	5×10^{-2}	2	10^{-6}	2×10^{-6}	9×10^{-4}		5×10^{-3}†			
		Lungs				3×10^{-7}	6×10^{-7}	2×10^{-5}	6				
		GI	7×10^{-4}	5×10^{-3}	0.3	10^{-7}	9×10^{-7}	5×10^{-5}	10				
78	Pt^{193}	Kidneys	3×10^{-2}	5×10^{-2}	2	10^{-6}	2×10^{-6}	7×10^{-5}		8×10^{-3}			
		Lungs				4×10^{-7}	6×10^{-7}	2×10^{-5}	6				
		GI	9×10^{-4}	6×10^{-3}	0.3	2×10^{-7}	10^{-6}	6×10^{-5}	10				
79	Au^{196}	Liver	0.4	0.6	20	2×10^{-6}	3×10^{-6}	8×10^{-5}		0.4			
		Kidneys	4×10^{-2}	6×10^{-2}	2	10^{-6}	2×10^{-6}	7×10^{-5}					
		Lungs				9×10^{-7}	10^{-6}	4×10^{-5}	20				
		GI	2×10^{-3}	10^{-2}	0.8	4×10^{-7}	3×10^{-6}	10^{-4}	30				

in which it is assumed the average daily intake is 2,200 cm^3 of water and 2×10^7 cm^3 of air. Values of T, E, m, and f used to obtain the data in the table were obtained from Table IV of the Internal Dose Handbook (*5*).

When exposure results from a single intake of a radioisotope, the critical body organ often is not the same as for the case of chronic exposure; frequently in the case of ingestion it is the gastrointestinal (GI) tract, and in case of inhalation it is either the respiratory or the GI tract. When a portion of the GI tract is the critical tissue, the amount of the radioisotope in the critical organ, $q\,f_2$, as given by Eq. 1 is replaced by the amount present at any time in the critical portion of the GI tract, $I_0\,e^{-0.693t/T_r}$, and the average dose rate, $W/7$, is integrated from the time of arrival, h_0, to the time of departure, h_1, of the radioactive material from the critical portion of the GI tract. The resulting dose, D, is given by

$$D = \frac{93}{100}\int_{h_0}^{h_1}\frac{W\,dt}{7} = \frac{93/100\;I_0\Sigma(\mathrm{RBE})E}{2.6\times10^{-3}\times7m'}\int_{h_0}^{h_1}e^{-0.693t/T_r}\,dt \tag{7}$$

$$D = \frac{51.1\;I_0\Sigma(\mathrm{RBE})E(h_1-h_0)}{m'G} \tag{8}$$

where $G = 1$ when the radioactive half-life $T_r \gg 1$. G is given by

$$G = \frac{0.693(h_1-h_0)}{(e^{-0.693h_0/T_r}-e^{-0.693h_1/T_r})T_r} \tag{9}$$

If it is assumed the mass of the material, m', in the critical portion of the GI tract irradiates the intestinal wall from half the solid angle for fraction $h_1 - h_0$ of a day, the maximum permissible concentration in water is given by

$$(\mathrm{MPC})_w^{\mathrm{GI}} = \frac{2I_0}{f_w 2{,}200} = \frac{1.8\times10^{-3}m'DG}{(h_1-h_0)f_w\Sigma(\mathrm{RBE})E} \tag{10}$$

In this case f_w is the fraction reaching the critical portion of the GI tract and is given by $f_w = (1 - f_1)$ where f_1 is the fraction going from the GI tract to the blood.

Usually, when a radioisotope is inhaled, some of it is swallowed. If a considerable portion enters the blood stream from the GI tract and is deposited in some organ, Eq. 6 must be used to find the $(\mathrm{MPC})_a$. If a portion of the GI tract receives the largest dose so that it is the critical tissue, Eq. 10 must be modified as follows

$$(\mathrm{MPC})_a^{\mathrm{GI}} = \frac{2{,}200f_w}{2\times10^7 f_a}(\mathrm{MPC})_w^{\mathrm{GI}} = \frac{2\times10^{-3}m'DG}{(h_1-h_0)f_a\Sigma(\mathrm{RBE})E} \tag{11}$$

where $f_a = 0.62\,(1 - f_1)$ is the fraction retained in the critical GI tissue, and the other terms are as defined previously. In most cases, i.e., where $T_r > \frac{1}{2}$ day, the lower large intestine

Maximum Permissible Values (continued)

				Ingested			Inhaled					
Z	Radio-isotope	Critical organ	0.043 rem/1 day	0.3 rem/1 wk	15.7 rem/1 yr	0.043 rem/1 day	0.3 rem/1 wk	15.7 rem/1 yr	Single (μc)	Continuous (μc/day)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
79	Au^{198}	Liver	0.2	0.3	10	8×10^{-7}	10^{-6}	6×10^{-5}		0.5
		Kidneys	10^{-2}	3×10^{-2}	1	5×10^{-7}	10^{-6}	4×10^{-5}		
		Lungs				7×10^{-7}	10^{-6}	6×10^{-5}	10	
		GI	6×10^{-4}	4×10^{-3}	0.2	10^{-7}	7×10^{-7}	4×10^{-5}	8	
79	Au^{199}	Liver	0.5	0.8	30	2×10^{-6}	4×10^{-6}	10^{-4}		1
		Kidneys	4×10^{-2}	7×10^{-2}	3	10^{-6}	2×10^{-6}	10^{-4}		
		Lungs				2×10^{-6}	3×10^{-6}	10^{-4}	30	
		GI	2×10^{-3}	10^{-2}	0.6	3×10^{-7}	2×10^{-6}	10^{-4}	20	
81	Tl^{200}	Muscle	5×10^{-2}	0.2	9	5×10^{-6}	2×10^{-5}	9×10^{-4}		0.6†
		Lungs				4×10^{-7}	10^{-6}	6×10^{-5}	8	
		GI	10^{-3}	9×10^{-3}	0.5	2×10^{-7}	2×10^{-6}	9×10^{-5}	10	
81	Tl^{201}	Muscle	0.3	0.7	30	3×10^{-5}	7×10^{-5}	3×10^{-3}		5†
		Lungs				2×10^{-6}	4×10^{-6}	2×10^{-4}	30	
		GI	9×10^{-3}	6×10^{-2}	3	2×10^{-6}	10^{-5}	6×10^{-4}	80	
81	Tl^{202}	Muscle	0.2	0.3	8	2×10^{-5}	3×10^{-5}	8×10^{-4}		4†
		Lungs				2×10^{-6}	2×10^{-6}	4×10^{-5}	10	
		GI	5×10^{-3}	3×10^{-2}	2	9×10^{-7}	6×10^{-6}	3×10^{-4}	40	
81	Tl^{204}	Muscle	0.2	0.2	3	2×10^{-5}	2×10^{-5}	3×10^{-4}		4†
		Lungs				10^{-6}	10^{-6}	3×10^{-6}	9	
		GI	10^{-3}	8×10^{-3}	0.4	2×10^{-7}	10^{-6}	7×10^{-5}	9	
82	Pb^{203}	Bone	0.6	1	60	3×10^{-5}	6×10^{-5}	3×10^{-3}		5×10^{-2}†
		Lungs				8×10^{-7}	2×10^{-6}	8×10^{-5}	20	
		GI	2×10^{-3}	10^{-2}	0.7	4×10^{-7}	2×10^{-6}	10^{-4}	30	
82	Pb^{210}	Bone	10^{-3}	10^{-3}	10^{-3}	5×10^{-8}	5×10^{-8}	6×10^{-6}		5×10^{-3}†
	$+dr$	Lungs				6×10^{-9}	6×10^{-9}	10^{-6}	6×10^{-2}	
		GI	3×10^{-6}	2×10^{-5}	10^{-3}	6×10^{-10}	4×10^{-9}	2×10^{-7}	4×10^{-2}	
84	Po^{210}	Spleen	2×10^{-3}	2×10^{-3}	10^{-2}	3×10^{-8}	3×10^{-8}	2×10^{-7}		10^{-4}
		Lungs				6×10^{-9}	7×10^{-9}	5×10^{-5}	8×10^{-2}	
		GI	3×10^{-6}	2×10^{-5}	10^{-3}	5×10^{-10}	4×10^{-9}	2×10^{-7}	4×10^{-2}	
85	At^{211}	Thyroid	4×10^{-6}	2×10^{-5}	10^{-3}	6×10^{-10}	4×10^{-9}	2×10^{-7}		6×10^{-6}
		Lungs				10^{-8}	7×10^{-8}	4×10^{-6}	trace	
		GI*	$>4\times10^{-6}$	$>2\times10^{-5}$	$>10^{-3}$	$>6\times10^{-10}$	$>4\times10^{-9}$	$>2\times10^{-7}$	trace	
88	$Ra^{226}+$	Bone	10^{-3}	10^{-3}	10^{-3}	7×10^{-8}	7×10^{-8}	7×10^{-6}		4×10^{-6}
	$55^{Ce}\,dr$	Lungs				10^{-9}	10^{-9}	3×10^{-9}	10^{-2}	
		GI	10^{-6}	8×10^{-6}	4×10^{-4}	2×10^{-10}	10^{-9}	8×10^{-8}	10^{-2}	

is the critical part of the GI tract; in this case, m', h_0, and h_1 are taken as 150 gm, $^{1}3_{24}$ day, and $^{3}1_{24}$ days, respectively.* When $T_r < 0.5$ day and > 0.08 day, the upper large intestine is the critical GI tissue, and m', h_0 and h_1 are taken as 135 gm, $^{5}_{24}$ day, and $^{1}3_{24}$ day, respectively.* For $T_r < 0.08$ day, the stomach is the critical GI tissue, and m' h_0, and h_1 are taken as 250 gm, 0 day, and $^{1}_{24}$ day, respectively.*

A third type of single exposure that must be considered results from inhalation of insoluble radioactive dust. In this case the lungs are the critical organs, and Eqs. 4 and 6 are used with the fraction retention, f, set equal to 0.125 and $T = 120\ T_r/(120 + T_r)$.

Since no criteria have been established by the National Committee on Radiation Protection for the maximum permissible single-exposure dose, D, the MPC values in water and air consumed over a period of one day have been calculated rather arbitrarily for the cases in which the resulting dose, $D = 0.043$ rem in a day, $D = 0.043 \times 7 = 0.3$ rem over a period of a week, and $D = 0.3 \times 52.2 = 15.7$ rem over a period of a year. It is apparent that the shorter the period over which the dose is integrated the smaller (or more conservative) are the maximum permissible values. It is suggested that the intermediate values corresponding to a dose of 0.3 rem be used for the operating maximum permissible values during the first week following an exposure, the larger values corresponding to a dose of 15.7 rem be used for emergency operations during the year following single exposure, and the smallest values corresponding to a dose of 0.043 rem be used for nonoccupational exposure during the first day after single exposure.

Values are given in the table for three cases: (1) the GI tract as the critical organ (using Eq. 10 for ingestion and Eq. 11 for inhalation), (2) inhalation of insoluble radioactive dust (using Eq. 6), and (3) for one or two other body organs (using Eq. 5 for ingestion and Eq. 6 for inhalation). In general the lowest values in each column of the table should be used as the maximum permissible values. If one wishes to know the maximum permissible amount (in μc) taken into the body in a single event, the values given in columns 4 through 9 in the table are multiplied by 2,200 in the case of ingestion and 2×10^{7} in the case of inhalation.

As a matter of special interest it might be indicated here that the National Committee on Radiation Protection is considering the selection of the GI tract as the critical tissue for chronic exposure, when a portion of the GI tract receives the greatest dose of radia-

* These values were furnished by a private communication from Dr. E. Pochin, Department of Clinical Research, University College Hospital Medical School, London, W. C. 1., October 9, 1953.

89	Ac^{227}	Bone	9×10^{-2}	9×10^{-3}	10^{-2}	10^{-8}	10^{-8}	10^{-8}	10^{-8}			10^{-8}
	$+dr$	Lungs				10^{-9}	10^{-9}		2×10^{-9}		10^{-2}	
		GI	5×10^{-7}	3×10^{-6}	2×10^{-3}	8×10^{-11}	6×10^{-10}	3×10^{-8}	3×10^{-8}		7×10^{-3}	
90	Th-nat	Bone	2×10^{-2}	2×10^{-3}	2×10^{-2}	4×10^{-9}	4×10^{-8}	1×10^{-6}	1×10^{-6}			8×10^{-5}
		Lungs				9×10^{-10}	9×10^{-10}	2×10^{-7}	2×10^{-7}		10^{-2}	
		GI	4×10^{-7}	3×10^{-6}	2×10^{-3}	7×10^{-11}	5×10^{-10}	3×10^{-8}	3×10^{-8}		6×10^{-3}	
90	$Th^{234}+$	Bone	8	9	80	2×10^{-6}	2×10^{-6}	2×10^{-5}	2×10^{-5}			0.4
	Pa^{234}	Lungs				4×10^{-7}	4×10^{-7}	5×10^{-6}	5×10^{-6}		5	
		GI	2×10^{-1}	10^{-3}	7×10^{-2}	3×10^{-4}	2×10^{-4}	10^{-3}	10^{-3}		3	
92	U^{233}	Bone	0.5	0.5	0.8	10^{-7}	10^{-7}	2×10^{-7}	2×10^{-7}			9×10^{-5}
		Lungs				7×10^{-9}	7×10^{-9}	2×10^{-8}	2×10^{-8}		9×10^{-2}	
		GI	3×10^{-6}	2×10^{-5}	10^{-3}	5×10^{-10}	4×10^{-9}	2×10^{-7}	2×10^{-7}		5×10^{-2}	
92	U-nat	Bone	0.3	0.3	0.4	6×10^{-8}	6×10^{-8}	9×10^{-8}	9×10^{-8}			3×10^{-5}
		Kidneys	6×10^{-3}	7×10^{-3}	5×10^{-2}	2×10^{-9}	2×10^{-9}	10^{-8}	10^{-8}			
		Lungs				4×10^{-9}	4×10^{-9}	9×10^{-9}	9×10^{-9}		5×10^{-2}	
		GI	2×10^{-6}	10^{-5}	6×10^{-4}	3×10^{-10}	2×10^{-9}	10^{-7}	3×10^{-7}		3×10^{-2}	
94	Pu^{239}	Bone	0.5	0.5	0.5	3×10^{-8}	3×10^{-8}	3×10^{-8}	3×10^{-8}			6×10^{-7}
		Lungs				6×10^{-9}	6×10^{-9}	9×10^{-9}	9×10^{-9}		8×10^{-2}	
		GI	3×10^{-6}	2×10^{-5}	10^{-3}	5×10^{-10}	4×10^{-9}	2×10^{-7}	2×10^{-7}		4×10^{-2}	
95	Am^{241}	Bone	0.4	0.4	0.4	8×10^{-8}	8×10^{-8}	9×10^{-8}	9×10^{-8}			4×10^{-5}
		Lungs				6×10^{-9}	6×10^{-9}	10^{-8}	10^{-8}		8×10^{-2}	
		GI	3×10^{-6}	2×10^{-5}	10^{-3}	5×10^{-10}	3×10^{-9}	2×10^{-7}	2×10^{-7}		4×10^{-2}	
96	Cm^{242}	Bone	0.4	0.4	0.8	7×10^{-8}	8×10^{-8}	2×10^{-7}	2×10^{-7}			8×10^{-5}
		Lungs				5×10^{-9}	6×10^{-9}	2×10^{-8}	2×10^{-8}		7×10^{-2}	
		GI	2×10^{-6}	2×10^{-5}	9×10^{-4}	4×10^{-10}	3×10^{-9}	2×10^{-7}	2×10^{-7}		4×10^{-2}	

* In cases where f_1 is given in ref. 5 as 1.0, MPC values based on GI tract as critical tissue would approach infinite value. Therefore, in these limiting cases, value recorded $\geq$ values calculated for critical organ using Eqs. 5 and 6.

† In these cases c in Eq. 12 was not known, so to be on the conservative side it was considered equal to one.

‡ Rate of water consumption was taken as 2,200 cm^3/day, breathing rate as 2×10^7, cm^3/day. To find permissible ingestion or inhalation in μc, multiply the $\mu c/cm^3$ values by 2,200 for water, 2×10^7 for air.

NOTE: The values given in this table for the dose rate of 0.043 rem/day may be considered as possible MPC values for continuous exposure when the GI tract is the critical tissue, since if one is exposed continuously at this rate the dose received each week will be 0.3 rem.

tion. If this decision is made, the values given in the table for the GI tract corresponding to a dose rate of 0.043 rem/day will replace some of the values now given in table III of Handbook 52 (*5*) when the values based on the GI tract are smaller and when the person is continuously exposed to air or water contaminated with radioactive material.

Total excretion per day of a radioisotope for chronic exposure that has resulted in an equilibrium condition in which the body has accumulated a maximum permissible body burden

No matter whether the internal dose of ionizing radiation results from a single exposure or from long continued exposure, it is difficult to obtain an accurate estimate of the body burden. This is one reason why an effort should be made to minimize such exposures. Sometimes estimates of the total body burden are made from the survey record of the average concentration of the contaminant in water or air that was taken into the body for a known period of exposure, but usually the best estimates of the total body burden of an individual are obtained from an analysis of the urine and/or feces. For the equilibrium case, as illustrated in Figs. 1, 2, and 3, the excretion of a radioisotope in a single day when a person carries the maximum permissible body burden of a radioisotope is given by

$$U = qf_2(1 - e^{-0.693\,T/T_b})T/T_bC \quad (12)$$

where U = total μc eliminated per day if the person is removed from exposure to further intake of the radioisotope during the period of excretion analysis, T_b = biological half-life in days, and C = ratio of amount eliminated from critical organ to the total amount eliminated. The other terms in Eq. 12 have the same definition as given previously. In general, C is not known. This difficulty can be partly circumvented by placing f_2 C = 1 and letting T and T_b apply to the effective and biological half-lives, respectively, of the entire body rather than of the critical organ. The last column of data in the table was obtained by application of Eq. 12, either to the critical organ or total body and making use of data from the Handbook of Internal Dose (*5*).

Fecal excretion of a radioisotope immediately following an intake of the maximum permissible amount in a single exposure

The fecal elimination following a single intake of the maximum permissible amount of a radioisotope is estimated and listed in column 10 of the table. Values are given for the two cases: (1) the insoluble radioactive dust was inhaled, and (2) the radioisotope was ingested. The equation used to find the fecal elimination during a few days following the single intake is

$$U = (1 - f_1)(\text{MPC})K \quad (13)$$

MPC values in Eq. 13 are taken from columns 5 and 8 of the table for which the dose is 0.3 rem during the week following a single exposure. In the case of ingestion, the smallest MPC value for the radioisotope is selected from column 5 and K is set equal to 2,200 cm^3/day. In the case of inhalation of insoluble dust, the proper value is selected from column 8 and K is set equal to $0.62 \times 2 \times 10^7$ cm^3/day.

In conclusion, it should be emphasized that the values given in the table are very preliminary and have not been considered by the National Committee on Radiation Protection. They are based on numerous sources of information that were examined by the authors with the valuable assistance of M. J. Cook and M. Wright of the health physics division of Oak Ridge National Laboratory. Where possible, values of m, f, f_1, f_2, T, T_b, etc., were taken from the Internal Dose Handbook (*5*).

* * *

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Recent Developments in Film Monitoring of Fast Neutrons

A modified nuclear-emulsion film packet, useful for neutrons up to 14 Mev, is proposed as a film dosimeter. Decreased fading of the latent image and a traverse scanning method increase the effective sensitivity of the film

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TO IMPROVE NEUTRON DOSIMETRY, a modified film badge and a new scanning technique have been developed. Aluminum shields and cellulose radiators make the film track population a measure of dose, independent of energy, and a sealed dehydrated film preserves the latent image for a longer period of time. Traverse scanning improves the effective sensitivity by a factor of ten.

The film badge used at this laboratory has pointed up the need for a modified technique. It comprised two dental-size gamma films of overlapping sensitivities, devised by Pardue *et al.* (*1*), plus a nuclear emulsion film for monitoring neutron exposure of personnel (*2*, *3*), suggested by K. Z. Morgan. Its shortcomings are inability to measure true dose or true flux, latent-image instability, and low sensitivity.

Neutron Dosimetry

The maximum permissible exposure (MPE) has been lowered for both thermal and fast neutrons. For thermal neutrons (n_{th}) Snyder (*4*) has calculated a permissible exposure in the range of 1,712 to 1,951 $n_{th}/cm^2/sec$ = 300 mrem/wk. On the basis of 1,800 $n_{th}/cm^2/sec$, this comes to 2.59×10^9 n_{th}/cm^2/40-hr wk, rather than the earlier value of 6.5×10^8.

Permissible fast-neutron (n_f) exposures have been calculated by Snyder and Neufeld (*5*) as a function of energy. The multiple-collision curve in Fig. 1 illustrates the dose in rep/n_f as a function of energy. On this basis, fluxes corresponding to MPE (30 mrep/wk) for some of the more commonly used neutron sources have been estimated. For neutrons of the fission spectrum (*6*), the flux is 50 $n_f/cm^2/sec$, or 7.2×10^6 $n_f/cm^2/wk$; for the Po-B spectrum (*7*), 37 $n_f/cm^2/sec$, or 5.33×10^6 $n_f/cm^2/wk$; and for the Po-Be spectrum (*8*), 31 $n_f/cm^2/sec$ or 4.46×10^6 $n_f/cm^2/wk$. These values replace the figures of 3.41×10^7 fast neutrons of the fission spectrum/cm^2/wk given in 1950 (*3*).

Personnel dosimetry for fast neutrons. The determination of the dose received by a person in the field is not a direct measurement of a primary neutron field. The presence of the body builds up the neutron density by backscattering; thus, the multiple-collision dose curve calculated by Snyder and Neufeld cannot be used, since they considered only the dose due to a neutron incident normally on the surface of the body. A film whose response is adjusted to the multiple-collision dose curve (*9*), if placed at a point reasonably removed from scatterers, would measure the dose a body would receive at that point; however, because of backscatter such a film placed on the body does not measure the correct dose.

TABLE 1—Effect of Phantom and Incidence Angle on Fast-Neutron Response

Distance of phantom from film (cm)	*Per cent of response relative to that at normal incidence without phantom including scatter from room*	
	Po-B	*Po-Be*
Normal position (A)		
No phantom	100	100
4	97 ± 6.7	111 ± 6.8
2	114 ± 7.2	124 ± 7.2
1.5	127 ± 7.6	131 ± 7.4
Parallel position (B)		
No phantom	69.4 ± 5.6	63.8 ± 5.1
4	76.7 ± 5.9	58.8 ± 4.9
2		64.3 ± 5.2
1.5	69.4 ± 5.6	66.4 ± 5.2
Shielded position (C)		
1.5	7.6 ± 1.2	27 ± 2.4
Scatter from room*	2.7	4.0

* Scatter from the room was determined by exposing film shielded by a 30-cm paraffin shadow cone, the apex of which was close to the source.

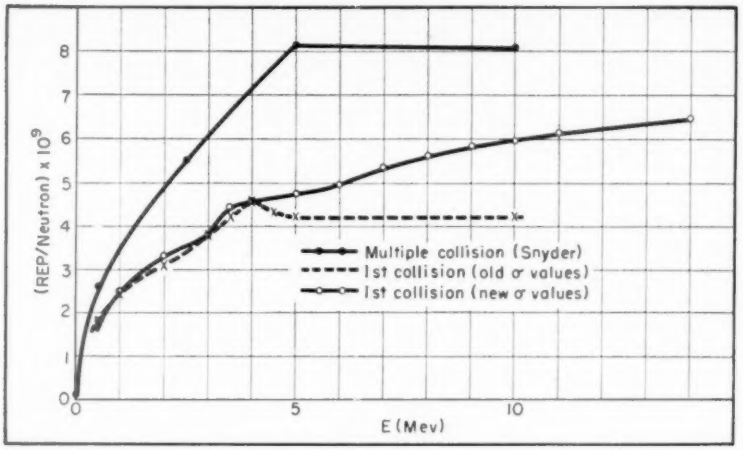

FIG. 1. Calculated neutron dose curves

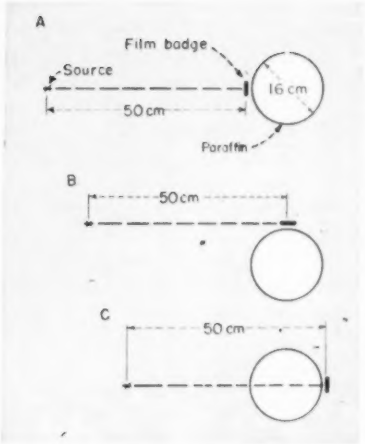

FIG. 2. Phantom arrangements to study shielding and backscattering

Also, a film worn by a person is moved about so that (a) the angle of neutron incidence varies, and (b) the degree of shielding by the body varies.

To determine the effect of shielding and backscattering, exposures were made in the presence of a cylindrical phantom of paraffin of 16-cm diameter. Figure 2 shows the phantom, film badge and source positions. The badges were placed 4 cm, 2 cm, and 1.5 cm from the surface of the phantom in the normal and parallel positions and 1.5 cm in the shielded position. The 1.5-cm position is the spacing due to the clip on the badge, and fixes the lower limit of separation from the wearer's body.

The results of all exposures, expressed in per cent response with respect to exposure normal to the beam without a phantom, appear in Table 1. The table shows that:

1. Backscatter and consequent buildup of neutron density is a function of energy, the higher-average-energy neutrons from Po-Be having a greater buildup than those from Po-B.

2. Lateral scatter is less than backscatter.

3. Only a small fraction of neutron flux penetrates the phantom, the fraction increasing with increasing energy.

In field use, body scatter remains a variable, depending on the separation of the film from the body surface. A representative value can probably best be approximated by calibrating films in the presence of a phantom set about 2 cm behind the film.

Body shielding is probably not as serious as might at first appear. The badge is ordinarily worn on the chest. Thus in general, while a source is being manipulated, it monitors the region of highest probable exposure. During a lengthy exposure, the experimenter moves about in the laboratory so that when the film is partially shielded, the corresponding part of the body is likewise shielded. Thus a representative average dose is usually measured.

To determine the effect of angle of incidence, a set of exposures to Po-B and Po-Be neutron sources was made, using the standard badge. The series consisted of placing the plane of the films normal to the beam, parallel to the beam, and rotating during exposure. With the Po-B source, the response at parallel incidence was about 63% that at normal incidence, and response when the film rotated during exposure was about 72% of that at normal incidence. With the Po-Be source, parallel exposure gave about 50% and rotated exposure gave about 65% of normal exposure.

Since the backscattered neutrons are recorded by the film, in addition to the primary ones, a first-collision, dose-type response should give a closer approximation to body dose than would the curves of Snyder and Neufeld.

The first-collision dose curve (*10*) was revised on the basis of the latest available cross-section values (*11*). The calculation included only neutron energy transfer due to elastic collision with all the atomic species present in soft tissue, as given by Lea (*12*). Gray and Read (*13*) have shown that other nuclear processes with Li-D neutrons contribute less than 1%, and Snyder and Neufeld (*5*) have computed that the thermalized component of fast-neutron beams contributes to the dose a maximum of 0.8% at 10 Mev and 4% at 0.48 Mev. Figure 1 presents the old and new first-collision dose curves and shows their relation to the multiple-collision dose curve.

NTA film as a dosimeter. The NTA film in the standard dental-type packet measures thermal neutron dose fairly reliably. Since the nitrogen content of the emulsion does not vary appreciably, and the film base and wrapper have negligible amounts of nitrogen, the proton track population due to the $N^{14}(n,p)C^{14}$ reaction varies only slightly from batch to batch. The cadmium in a portion of the badge serves to eliminate thermal neutrons and, consequently, protons induced by thermal neutrons from the portion of the film used for measuring fast-neutron dose.

On the other hand, with fast neutrons, the production of recoil protons is a function of energy because of the variation both in collision cross section and proton range with energy. The recoil-proton tracks comprise:

1. Protons ≥ 0.25 Mev, which are formed in the emulsion.

2. Protons formed in the plastic film base and entering the emulsion with a residual energy ≥ 0.25 Mev.

3. Protons formed in the film wrapper or other extraneous hydrogenous material, and reaching the emulsion with an energy ≥ 0.25 Mev.

A proton of 0.25 Mev has the energy required to generate a track of three grains—the minimum needed for recog-

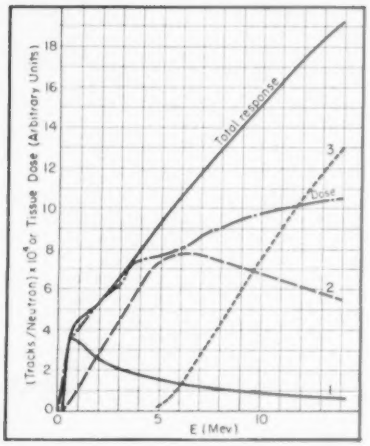

FIG. 3. Neutron response of unmodified film badge

nition. As will be shown later, variation of track density with energy is different from the dose-rate variation with energy and depends on the surrounding media. With appropriate modifications, the method of Hurst, *et al.* (*10*), for calculating the response of a counting-rate neutron dosimeter, is applicable to the evaluation of film response. The track population due to protons generated in the emulsion may be computed in the same manner as that of the hydrogenous gas in a chamber. Curve 1 in Fig. 3 is a plot of tracks/neutron as a function of E for a 30μ emulsion layer. Fraction 2, due to protons generated in the film base (curve 2 in Fig. 3), is analogous to the response of a proportional counter with a thin-plane-slab proton radiator.

If curves 1 and 2 are added, giving the response of the emulsion when exposed through the film base as a function of E, the shape of the composite curve (not shown) approximates the dose curve fairly well up to $E = 3.5$ Mev. Beyond this energy the response deviates from the dose-energy curve, the dose becoming too small for $E > 7$ Mev. This is the type of response that would be obtained if the film were completely shielded from externally produced protons by a nonhydrogenous substance. The source of fraction 3 of the track population is treated as a shielded radiator, the shield thickness being evaluated in terms of the energy (Mev) of a proton that just can penetrate the shield. The film base is, then, 4.37 Mev thick.

In the badge used previously, the film wrappers and the gamma film placed before the NTA film supplied a thick hydrogenous radiator. The organic substance in front of the emulsion totaled 227 mg/cm², which is approximately 14 Mev thick in terms of proton range. Calculating fraction 3 for the energy range above 4.37 Mev, one obtains curve 3 of Fig. 3 as the proton contribution of this radiation when the neutron flux is normal to the film base. Figure 3 also illustrates the total response of this badge, indicating that the track value per neutron at 14 Mev is almost twice that called for by the first-collision dose curve.

Thus, a radiator must be designed such that enough protons are supplied by neutrons of 3.5 to 14 Mev to compensate for the discrepancy between the composite of curves 1 and 2 and the dose curve in this range, yet not too many, as in the total response curve of Fig. 3. This can be done by using a hydrogenous radiator, such as an unsized paper, shielded by a nonhydrogenous substance, such as aluminum. Paper is chosen as the radiator because it is largely pure cellulose and, therefore, its response can be calculated to a good degree of approximation, and it is available in any thickness. Aluminum is chosen as the nonhydrogenous substance because its capture cross section is small for moderate and high-energy neutrons, it is available in any thickness, and it is a flexible metal, easy to handle.

The shielded-radiator method provides a means of calculating the proton contribution of each hydrogenous layer of such a radiator. The shielding properties of the radiator can be calculated by the method of Hirschfelder and Magee (*14*), and aluminum-shield thicknesses can be evaluated from Bethe's proton ranges (*15*). Specifications for such laminations can be determined to accommodate any neutron energy of established dose rate.

A calculation has been made of the radiators and shielding required to

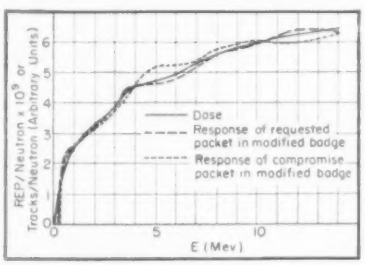
REP/Neutron x 10⁹ or Tracks/Neutron (Arbitrary Units)
Dose
Response of requested packet in modified badge
Response of compromise packet in modified badge
E (Mev)

FIG. 4. Film response fitted to calculated first-collision dose

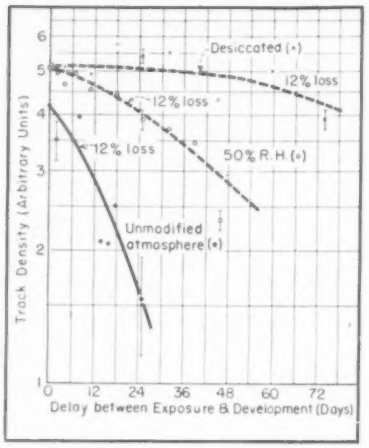

FIG. 5. Effect of relative humidity on latent image stability

make the film response correspond to the first-collision dose curve. An excellent fit can be obtained by reducing the film-base thickness from 0.008 in. to 0.006 in. = 17.5 mg/cm² (3.3 Mev), then packaging with several layers of aluminum and paper. The response of this packet is shown in Fig. 4.

Discussion of this modification with J. Spence and W. F. Swann of Eastman Kodak's research personnel disclosed that, besides introducing rather difficult manufacturing problems, a film on a thinner base would be more subject to curl and, in general, more difficult to handle. A compromise packet was assembled using the original film base (4.37 Mev thick). If such a packet is placed in a badge with additional shields and radiators, as shown in Table 2, the response represented by curve 3 in Fig. 4 is obtained. This curve does not deviate more than 10% from the dose curve in any energy region, and only a few percent throughout most of the range, thus in general introducing few errors as large as the reading errors.

The shield and radiator laminations listed in Table 2 are symmetrical to the plane of the emulsion. Thus, while angular independence cannot be achieved, response in a reversed position is equal to that of normal incidence. In this way, the orientation of the badge becomes less important than if it were completely directional. An approximate response check was made by exposing one of the new packets in a modified badge, as shown in Table 2, and one of the old packets in an unmodified badge to a Po-Be source. Expected responses were calculated on the

basis of the Po-Be spectrum (*8*). Calculated response of the new packet was 88.6% of the response of the old badge. Track count gave 84.8 ± 7.3%.

Latent Image Stability

The relative instability of latent images of tracks in nuclear emulsions has been a troublesome characteristic of neutron film dosimetry. The low sensitivity of nuclear films could be enhanced by a longer exposure period, provided the emulsion could be depended on to indicate an integrated exposure. Early measurements (*3*) indicated a 50% loss in track populations in 20 to 23 days if fission neutrons were used. In practice, a 12% correction is made in calibration values to allow for probable track loss in the course of the week that films are being worn.

Several observers (*16–18*) have noted that high relative humidity is a major factor in rapid latent image loss. The converse effect was tested. After a uniform exposure to Po-Be neutrons, a group of films was stored at 24° C and 50% relative humidity, while another group was stored at 24° C in a desiccator over "Drierite" and periodically developed. Results of these tests, together with earlier results for storage at unmodified ambient conditions, appear in Fig. 5. As can be seen, controlling the relative humidity at 50% increased the retention of 50% of track population from about 20 days under uncontrolled conditions to about 50 days. Desiccated films retained well over 50% of tracks at 74 days—the end of the test period. If one compares the period for 12% loss, a more practical criterion, one arrives at 5, 16, and 64 days, respectively. Thus, desiccated films could increase the monitoring periods, giving better statistics.

The moisture-proofing of the films could be accomplished in one of two ways: either the manufacturer might be persuaded to desiccate and seal each film packet or an airtight badge containing a desiccant could be devised.

Reading Technique

The microscopy technique used at the Oak Ridge National Laboratory (*3*) consists of reading 12 discrete fields each on the Cd-shielded and the unshielded portion of each film, using a magnification of 950× with oil immersion and dark-field illumination. (The difference between readings is considered to indicate thermal neutron exposure.) The area of one field is 2×10^{-4} cm², and the area scanned in each case is 0.0024 cm². As one week's MPE of n_f produces 2.5×10^3 to 3.0×10^3 tracks/cm², such an exposure is indicated by 6 or 7 tracks in the total area scanned. A week's MPE of n_{th} produces a slightly larger track density. In either case, the statistical reliability is poor and an estimate of a fraction of a week's MPE is meaningless.

TABLE 2—Final NTA-Film Packet

Material	*Thickness (mg/cm²)*	*Energy of proton whose range equals cumulative thickness of material to emulsion (Mev)*
Cellulose (or front film)	76	14
Aluminum	85	11.05
Cellulose	24.2	8.0
Cellulose (film wrapper)*	10.3	6.6
Aluminum*	27	5.9
Film base*	28.5	4.37
Emulsion*	—	—
Blank film*	28.5	4.37
Aluminum*	27	5.9
Cellulose (film wrapper)*	10.3	6.6
Cellulose	24.2	8.0
Aluminum	85	11.05
Cellulose	76	14

* These constituents are present in the packet as supplied by the manufacturer.

The improved technique consists of scanning a measured traverse instead of discrete fields. This method eliminates counting the number of fields scanned, and also since the traverse is essentially a parallelogram, minimizes uncertainty due to edge effects.

First a 44× dry objective and two 10× wide-field eyepieces were tried. This combination gave a field diameter of 0.045 cm. When the stage stops were set to allow a travel of 1.11 cm, the area of the traverse was 0.05 cm². This is about 20 times the area of the 12-field method, and with 2,500 tracks/cm² (due to one week's MPE), 125 tracks are counted rather than 6. This combination was found to be reproducible to within statistical accuracy when tested by three independent observers on film developed immediately after exposure, but if the film was fogged or the tracks had degenerated by fading, readings were not reproducible. A compromise arrangement was then tried. Reverting to the 95× oil-immersion objective, and using 10× wide-field eyepieces, the traverse method was retained. This combination gave a field diameter of 0.019 cm. Thus, if the stops are set to allow a travel of 1.51 cm, the area scanned is 0.028 cm², or 12 times that of the 12-field method. With 2,500 tracks/cm², about 72 tracks appear per traverse. Including time handling, the over-all time required per film is only about twice that of the older method.

Random "background" tracks, due to cosmic rays, alpha-active contamination of film or wrapping materials, or diffusion of radon into the packet are minimized by this method.

Conclusions

The unmodified neutron film badge and packet is sufficiently accurate as a practical dosimeter if used to monitor exposure to neutrons of the fission spectrum, where the percentage of neutrons above 3.5 Mev is small, or to monitor Po-B neutrons, which group closely about 2.5 Mev, where the response curve corresponds to the dose curve. The modified film packet in an unmodified badge gives a response that does not deviate appreciably from the dose curve below 10 Mev, and consequently may be used to monitor exposure to neutrons from a Po-Be source where only a few per cent of the total neutrons have energies greater than 9 Mev. However, for monitoring neutrons in the range of 10 to 14 Mev, such as may occur in the vicinity of accelerators, it is recommended that the modified film packet be used in the modified badge.

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Betatron X-Rays:

How Much Concrete for Shielding?

Here are the data needed to calculate thickness of concrete for shielding betatrons operating at energies up to 38 Mev. Comparison of data with theory indicates the possibility of extending the calculations to 100 Mev

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BETATRONS ARE USEFUL AS tools in research, industry and medical radiology. As new models of higher energy and greater output have been produced, the thicknesses of radiation protection barriers have had to be estimated from data obtained from existing installations and narrow-beam attenuation curves. A need has arisen for fundamental data required for the design of protection from the useful beam.

Since protection barriers made of concrete are usually the most practical and economical throughout the energy range of betatrons, concrete was the only barrier material considered in these experiments.

Absorption, Attenuation

X-rays, in passing through a barrier, can undergo three types of interaction with the absorbing medium. In the process they lose a part or all of their energy. These interactions are commonly known as the photoelectric, Compton and pair-production processes, and their cross sections depend on the atomic number of the absorbing material and the energy of the incident photon. This dependence is such that, with concrete as the attenuating material, the photoelectric absorption is by far the most important for photons with energies below 0.1 Mev. The Compton process is predominant in the range from 0.1 to 10 Mev, and pair production is most significant above 20 Mev (*1*).

In both pair production and photoelectric absorption the photon loses all its energy in the interaction. The situation is quite different in the Compton effect, wherein the photon is scattered and thereby degraded in energy, rather than completely absorbed.

Thus, if the photoelectric and pair-production processes were the only mechanisms of absorption and if the radiation subsequently emitted by the photoelectrons and pairs could be neglected (as is the case in concrete for photon energies up to 100 Mev) then the photon flux would be a simple exponential function of the depth of penetration for incident photons of any energy. The net attenuation coefficient under these circumstances would be the sum of the photoelectric and pair-production absorption coefficients.

However, with Compton scattering also contributing to the attenuation, the Compton absorption coefficient generally cannot be added in and the result used as the total attenuation coefficient in a simple exponential function. The Compton scattered photons are not really lost and can contribute to the transmitted flux.

It is possible to measure X-ray penetration in such a way that virtually no scattered photons will reach the detector. This can be done with a well-collimated beam of photons incident on the front face of a wall, and a point detector in the line of incidence far behind the wall. Such an arrangement is described as having narrow-beam geometry (*2*), and in this special case photon flux falls off exponentially with depth.

As the beam diameter (or the detector area) is increased beyond a certain size, the contribution from the scattered photons reaches its maximum value and the system has then undergone the change from narrow-beam to broad-beam conditions. The increase in dose in broad-beam geometry over that in narrow-beam geometry is called the "build-up" and the ratio of the transmitted dose in broad-beam geometry to that in narrow-beam geometry is termed the "build-up factor."

Betatron photon spectra are such that for operating energies below 100 Mev a significant fraction of the photons is emitted in the energy range for which Compton scattering is dominant. Thus, the attenuation of the betatron beam by a protective concrete barrier will depend on whether broad- or narrow-beam geometry prevails. This, in turn, depends on how the diameter of the irradiated area of the barrier compares with the size of the beam necessary to fulfill broad-beam conditions.

The size of the irradiated area will depend on the betatron operating energy, the betatron target thickness, and the distance from the target to the barrier. With an infinitely thin betatron target, the electrons are monodirectional and the radiation is almost wholly contained in a cone with a half aperture of u/E radian, where u is the rest energy of an electron and E the

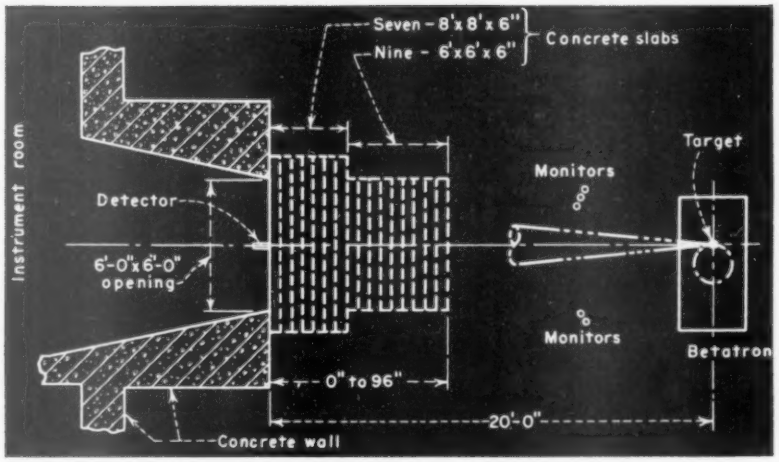

FIG. 1. Plan view of experimental layout

total energy (including the rest energy) of an electron hitting the target.

With targets of finite thickness (such as are used in a betatron) the electron beam is scattered in the target so that angular distribution of the radiation is broader than for the thin target case. For example, with a tungsten target 5 mils thick, the angle at which the radiation intensity falls to one-half of the value at 0 deg has been calculated to be $2.3/E$ radians, where E is the total electron energy in Mev (*3*). This should be compared with the value $0.51/E$ for the case of the infinitely thin target.

The approximate diameter of the irradiated area is determined by multiplying the angle (in radians) of the cone containing the radiation by the distance between target and barrier.

Information on what constitutes a maximum broad beam was obtained by independently varying the size of the irradiated area and the lateral position of the detector.

In experiments run with betatron energies from 6 to 20 Mev and a target-to-barrier distance of 20 ft, the geometry can be considered as broad-beam. As betatron energy is increased, there are three effects that cause attenuation to approach exponential form: (1) the percentage of photons in the Compton energy range decreases, (2) the average energy lost per Compton collision is an increasingly larger fraction of the incident photon energy as higher incident photon energies are considered, so that the Compton process is more like a total absorption process, and (3) the betatron beam is narrower at higher energies. Thus, the build-up factor can be expected to approach unity as the operating energy is increased. This is confirmed by a comparison of the 38-Mev transmission data with that calculated using exponentials, suitably weighted to account for the betatron spectrum. This type of "narrow beam" calculation has been carried out by Maynecord (*4*) for several energies up to 50 Mev, and by the authors at selected energies up to 100 Mev. This comparison is shown in Fig. 5 and will be discussed later.

Units

The most important quantity in determining protection requirements is the absorbed dose in air or tissue. The International Commission on Radiological Units has established as the unit of absorbed dose the "rad," which is equal to 100 ergs/gm imparted to matter by ionizing particles at the place of interest (*5*). In this experiment the specific ionization (in esu/cm^3) in the air behind the barrier was measured with ionization chambers.* It may be converted to rads in air by using the conversion factor, 1 esu/cm^3 = 0.83 rads in air. The conversion to rads in air was selected since the weekly permissible dose also is expressed as rads in air. The accepted value is set at 0.3 rads in air per week (*6*).†

Attenuation in concrete is determined by measuring the specific ionization in air behind varying thicknesses of material. A special problem arises in connection with the measurement with zero barrier thickness. Almost all the specific ionization in air measured behind a barrier is caused by the flux of electrons from the barrier. The air between the betatron target and the detector does not provide electronic equilibrium at the distances commonly used, so that the readings obtained in an ionization chamber with no barrier present are not directly comparable with those obtained behind the barriers (all of which exceeded equilibrium thickness). To overcome this difficulty, the reading for zero barrier thickness was made to correspond to what would be measured with an r-meter embedded centrally in a 11.5-cm Lucite cube.‡ The ratio of the reading behind the barrier to the reading for zero barrier thickness indicates the ratio of absorbed dose in air to which personnel would be exposed at the position of the detector with and without the barrier.

EXPERIMENTAL ARRANGEMENT

Figure 1 is the plan view of the experimental layout. The detectors (discussed later) were always mounted touching the first barrier and in a vertical row with their axes parallel to the center line of the beam. For all measurements at least three detectors were used, and for determining beam shapes as many as twelve were uniformly spaced across the beam. Their position could be accurately reproduced between readings.

The 8 × 8-ft concrete absorbers overlapped the opening in the wall by 1 ft on all four sides.

Additional shielding from scattered radiation was provided by stacking small concrete blocks around the bottom and two sides of the absorbers and

* The Bakelite $\frac{1}{8}$-in. wall of the ionization chamber causes a slight change in the electron flux. The ionization measured in a cavity in Bakelite of electronic equilibrium thickness is 10–15% less than that measured in a cavity in concrete that is also of equilibrium thickness. Since $\frac{1}{8}$-in. of Bakelite is not nearly thick enough for electronic equilibrium, the ionization measured is due chiefly to the electrons from the concrete and only partly from the Bakelite. Since the Bakelite thickness is small compared to the thickness necessary for electronic equilibrium it will produce an effect of no more than a few per cent.

† The exception to this is made when under these conditions the absorption in tissue would exceed 0.5 rads per week. The weekly permissible dose is then governed by this latter figure.

‡ A Lucite cube of this size produces maximum ionization, to within 10%, at all betatron energies from 6–50 Mev (*3*), and is nearly tissue-equivalent.

placing a row of lead bricks across the top of the absorbers. Detectors placed at the cracks indicated a negligible amount of radiation leakage.

A set of radiation monitors placed on each side of the main beam completed the experimental layout.

Concrete Barriers

The concrete barriers consisted of seven 8-ft × 8-ft × 6-in.-slabs and nine 6-ft × 6-ft × 6-in.-slabs. Attenuation in the first 42 in. was determined using the 8-ft slabs, and the remaining 54 in. of absorber was made with the 6-ft slabs.

All slabs were reinforced with ½-in. steel rods. The reinforcement on the 8-ft slabs was arranged to leave the central 6-ft square free from steel. Since only a very small fraction of the radiation was incident upon the rods, no allowance for their presence was needed. The 6-ft slabs were reinforced throughout with ½-in. rods spaced approximately 6 in. apart.

Since the exact positions of these rods were unknown, an estimate of their maximum and minimum effective thickness in terms of concrete was made. The attenuation curves were then plotted using the mean of those estimates with a resulting inaccuracy of ±2% in determining the thickness in the ranges between 42 in. and 96 in.

The effective thickness of the concrete slabs in terms of concrete of 147 lb/ft³-density was determined by weighing each block and measuring its area. Allowances were made for the volume and weight of the steel reinforcing rods.

Radiation Instruments

Radiation instruments were used to monitor the primary beam and measure the transmitted beam. The former are called monitors and the latter are called detectors.

Detectors. Three groups of detectors were used to cover the expected ionization rates, which ranged from 10 esu/cm³/min to below 5×10^{-5} esu/cm³/min.

Conventional 200-mr Victoreen pocket chambers were used for the range from 10 to 10^{-2} esu/cm³/min, 10-mr Victoreen chambers for 5×10^{-2} to 5×10^{-4} esu/cm³/min, and a modified 10-mr chamber from 10^{-3} to 5×10^{-5} esu/cm³/min. These detectors are basically integrating devices that read total dose delivered in a given exposure. They were chosen because of their small dimensions, ease of reading, and because the quantity they measured could be converted to absorbed dose units (rads). It was possible in the majority of runs to limit the exposures to less than 10 min.

TABLE 1 — Dose Conversion

Maximum betatron energy (Mev)	f_E*
6	0.746
10	0.662
20	0.526
30	0.438
38	0.404

* The ratio of ionization produced in a 25-r meter centered in a 11.5-cm cube of Lucite to the ionization produced in a 25-r meter covered by a ⅛-in. lead cap (*3*).

In the first two ranges of dose rate, the chambers were charged and read in a conventional Victoreen charger-reader apparatus. However, in the lowest range, the dose rate behind the barrier was so low that long exposures would have been necessary to get readable deflections by the usual method. Therefore, a method was devised to increase the readable range of the chambers by a factor of 10 by measuring the small changes in charge instead of the total charge.

The technique of measuring this charge difference is simple in principle. Two condenser-type chambers of the same electrical capacity were charged to the same voltage but with opposite polarity. One chamber was placed in the radiation field and underwent a slight discharge. Then the center electrodes of the fully charged and slightly discharged chambers were connected together. The resulting charge on the system of condensers was equal in quantity but opposite in sign to that lost through discharge in the radiation field. This net charge was measured with a vibrating-reed electrometer. The observed deflection was proportional to the charge and, in turn, to the ionization produced by the radiation.

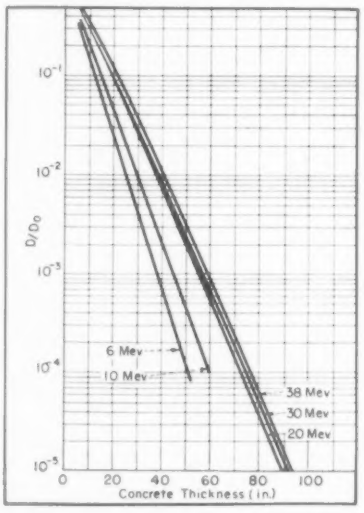

FIG. 2. Attenuation curves for 147-lb/ft³ concrete

The electrometer was calibrated directly in terms of esu/cm³. The charging voltage of approximately 150 volts for all chambers was kept constant to one part in 10,000. The chambers were adjusted to the same capacity by varying the lengths of the charging stem.

The limit of accuracy by the divided-charge method was 10% as compared with 5% by the other methods. The larger uncertainty in this method is due principally to the erratic leakage rate in the detectors and the variation in charge placed on the condenser due to contact capacitance.

The chambers were all calibrated in terms of esu/cm³. Leakage tests were made frequently and any chamber evidencing a leakage as large as 1% of full scale per hour was rejected.

Monitors. Fluctuations in betatron output made it necessary to monitor each exposure. For this purpose, a 0.25-r, a 2.5-r, and a 25-r Victoreen r-meter were located at fixed positions between the barrier and the betatron. They were off to one side of the center of the X-ray beam.

The number of esu/cm³ measured by the monitors for a given exposure was observed corresponding to the number of esu/cm³ collected in a standard 25-r Victoreen chamber covered with a ⅛-in. lead cap and placed in the center of the X-ray beam and at the same distance from the target as the detectors.

A calibration factor then was determined for each monitor at each operating energy. The monitors then served as secondary standards to which the detector reading behind the barrier could be compared. Two other chambers (of 25-r and 0.25-r size) were placed on the opposite side of the beam as a check on the first set. The ratio of the readings of the two sets was sen-

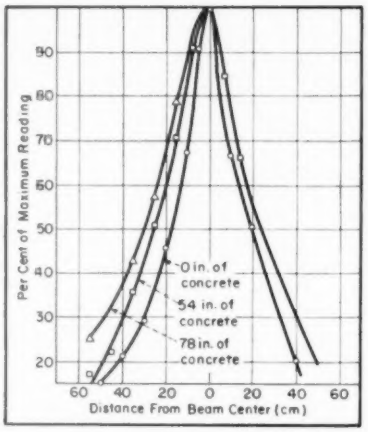

FIG. 3. Distribution of dose behind barriers. Target-to-detector distance was 611 cm (38 Mev)

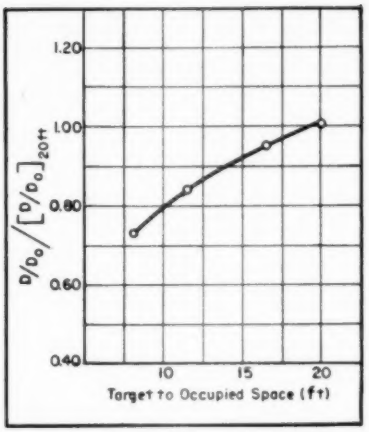

FIG. 4. Change in transmission as function of target-to-detector distance. Each point is an average of data taken at 38 Mev with concrete barriers 24 and 42 in. thick

sitive to any shift in the beam position.

Energy measurement, control. The betatron operating energy was held steady within less than ±1% by means of a recently-developed energy control device (7). This device was calibrated in energy against known photo-nuclear thresholds.

RESULTS

The results of the attenuation measurements are presented in graphical form in Fig. 2. The ordinate is the ratio D/D_0, where D is the absorbed dose in air directly behind the barrier at a given distance from the target, and D_0 is the dose calculated for a Lucite cube at the same point with no barrier present (see section on "units" describing Lucite cube used to obtain equilibrium). Experimentally, D_0 was obtained by exposing a 25-r chamber covered with a ½-in. lead cap and then, by means of Table 1 (5), converting the readings to the values expected inside an 11.5 cm Lucite cube.

The ratio D/D_0 may be expressed as

$$D/D_0 = \frac{d}{d_0 R f_E}$$

where d and d_0 are the corresponding specific ionizations (esu/cm³) measured by the detector behind the barrier and by the monitors on the side of the unobstructed beam. R is the calibration factor experimentally determined for each monitor at each operating energy, and is the ratio of the readings of the lead-capped r-meter at the center of the open beam and of a given monitor at one side of the beam (see "monitors"). Values of f_E, tabulated in Table 1, convert the standard r-meter reading with a lead cap to the reading in a 11.5-cm Lucite cube. The abscissa (Fig. 2) is the thickness of the barrier in inches of concrete having a density of 147 lb/ft³ (2.35 gm/cm³). Attenuation curves for operating energies of 6, 10, 20, 30, and 38 Mev are plotted on the same graph. Because of the lower output of the betatron at 6 and 10 Mev, these curves could not be extended as far as the others.

The use of the curves in shield design is straightforward. It is necessary to measure the dose rate from the machine, with no intervening barrier, using the readings either from an r-meter embedded in Lucite or from an r-meter in a lead cap corrected in accordance with Table 1. A knowledge of the weekly work load, and the permissible weekly dose will determine the attenuation required. The curves then indicate the thickness of barrier required to provide this attenuation.

Angular Distribution

The useful beam of a betatron is sharply defined and, particularly for a fixed installation, the main shielding can be concentrated over a small area determined by the beam size. Thus, it is important to know how beam size varies with the thickness of the barrier. That some increase with thickness will occur is to be expected from the broad-beam build-up phenomena. Accordingly, the distribution of dose behind the barrier was measured for several thicknesses of concrete. Figure 3 gives the results for 0, 54, and 78 in. of barrier at 38 Mev.*

Target-to-Barrier Distance

Some change in the transmission through a barrier may be expected as the distance between barrier and source (target) is varied. This is due mainly to changes in geometry influencing the broad-beam effect.

Figure 4 shows the change in D/D_0 plotted as a function of the distance between the target and the far face of the barrier where the detector was located. The readings were normalized to the value of D/D_0 at 20 ft. Since the results at 24 and 42 in. were nearly identical, average values were plotted.

The data show that $D/D_0 < 1$ for distances less than 20 ft, and that computations based on the curves of Fig. 2 will err slightly in the direction of providing over-protection. For distances greater than 20 ft, extrapolation indicates that $D/D_0 > 1$ and an error may be introduced in the opposite direction. However, it is to be expected that the slope of this curve will monotonically approach zero at target-to-occupied-space distances that are sufficient to provide maximum broad beam conditions. Thus the error will probably not exceed about 20% for target-to-occupied-space distances less than 30 to 40 ft. In either case, the error in barrier computation amounts to less than 2 in. of concrete.

COMPARISON

During these experiments, the betatron could be operated only up to 38 Mev. Consideration was given to the possibility of extrapolating the data for use at higher energies.

The narrow-beam attenuation curves of Fig. 5 were calculated for photon energies of 10, 40, 70 and 100 Mev. The last three are nearly identical. To check the computational method, the 40-Mev narrow-beam curve was compared with experimental data obtained at 38 Mev. While not agreeing perfectly, the curves are similar except for a uniform displacement corresponding to about 1 half-value layer of concrete (~5 in.) for thicknesses >20 in.

Accordingly, it is reasonable to as-

* Increase is not always as marked, depending on type of barrier and energy of radiation. See, for example, the work of Kantz and Hofstadter (8) whose experiments with 118- and 154-Mev electrons in copper indicate a lesser spreading of the beam.

sume that the 38-Mev experimental data may be applied for energies up to 100 Mev without introducing an uncertainty greater than 1 half-value layer in barrier computations.

A more complete comparison of the experimental data with theory was made by direct calculation of the transmitted intensity following the methods developed by Spencer and Fano (*9*). This calculation assumes an infinite parallel beam of X-rays striking an infinitely-extended barrier and a negligible amount of photons scattering out of the incident face. The calculations can be simplified somewhat if interest is only in X-ray dose at a point in the barrier. This dose is calculated from a reduced transport equation by numerical integration methods.

A comparison of experimental and calculated attenuation curves is shown in Fig. 6 for a betatron energy of 30 Mev.

It must be pointed out that in the theoretical curves it was assumed that the dose or energy absorbed in a given depth came from the X-rays absorbed at that depth. However, at these betatron energies the range of the electrons resulting from the disappearance of the photon is significant compared to the mean free path of the X-rays. Thus, the energy absorbed by the concrete from a given photon is spread out along the path of the electron. The effective penetration of the radiation energy is therefore slightly greater than shown in Fig. 6. The decrease in effective attenuation penetration is equivalent to that of about 0.5 inches of concrete for 30-Mev betatron X-rays (*10*).

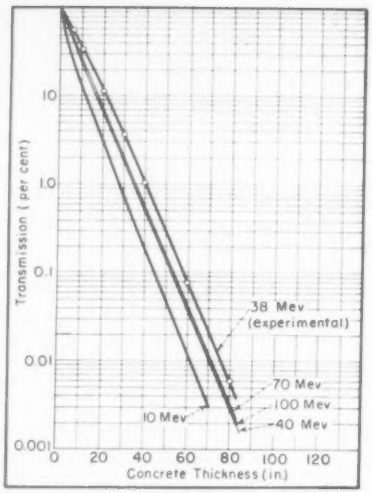

FIG. 5. Narrow beam attenuation curves

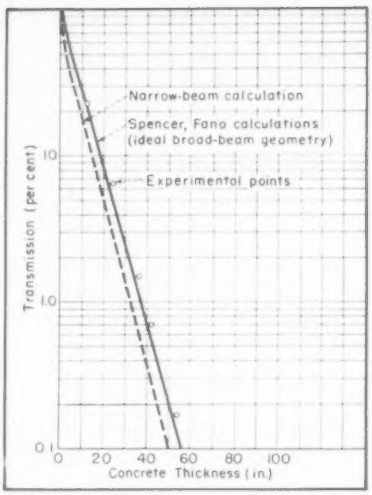

FIG. 6. Broad beam attenuation curves for a 30-Mev betatron

TABLE 2—Betatron Shielding Requirements

Betatron output at 3 ft from target (rads/min)*	*Distance to occupied space (ft)*	*Attenuation required to reduce dose rate to 0.3 rads/wk for a 48-hr wk (D/D_0)*	*Barrier† thickness required for protection (in.)*				
			Betatron energy (Mev)				
			6	*10*	*20*	*30*	*38*
10^3	25	7.2×10^{-6}	..	..	93	94	96
	50	3.0×10^{-5}	..	..	82	85	86
	100	1.2×10^{-4}	53	61	73	74	75
10^2	12.5	1.8×10^{-5}	..	..	87	89	90
	25	7.2×10^{-5}	56	65	77	79	80
	50	3.0×10^{-4}	48	55	65	67	68
	100	1.2×10^{-3}	40	46	55	57	58
10	12.5	1.8×10^{-4}	51	59	70	72	73
	25	7.2×10^{-4}	43	49	59	61	62
	50	3.0×10^{-3}	34	40	48	50	51
	100	1.2×10^{-2}	26	30	37	39	40
1.0	12.5	1.8×10^{-3}	38	43	52	53	54
	25	7.2×10^{-3}	30	34	41	43	44
	50	3.0×10^{-2}	21	24	29	31	32
	100	1.2×10^{-1}	14	16	18	19	20

* Measured by dose absorbed in air in center of an 11.5-cm Lucite cube.
† Concrete of 147-lb ft^3 density.

SUMMARY

The data presented in this paper provides information to calculate radiation protection from the useful beam of betatrons and betatron-synchrotrons operating in the energy range between 6 and 38 Mev. Data are not yet available above 38 Mev, but comparison with theoretically obtained curves indicates that the 38-Mev data probably give a good first approximation for attenuation in concrete up to 100 Mev. Table 2 shows shielding requirements for representative betatron operating outputs for several distances from target to occupied-space at various operating energies.

* * *

This work was supported by the Division of Biology and Medicine of the U. S. Atomic Energy Commission. The authors wish to extend their thanks to H. O. Wyckoff and W. Miller for their helpful and penetrating discussions of this work as well as to H. W. Koch and E. Fuller and the NBS betatron group for their able assistance and suggestions during the experimental phase. L. V. Spencer's interest in the theoretical calculations was very helpful, and the help of John Hopfield was very much appreciated.

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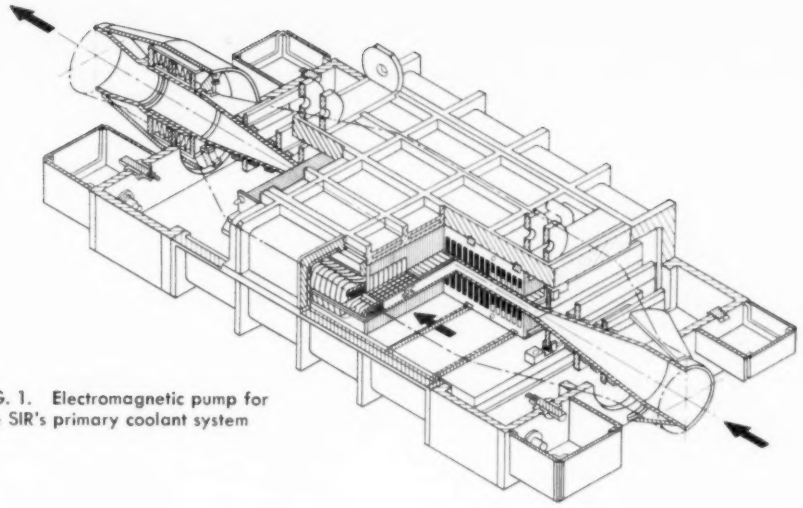

FIG. 1. Electromagnetic pump for the SIR's primary coolant system

Testing Electrical Insulation for Use in Gamma-Ray Fields

Submarine Intermediate Reactor's coolant pump will be subjected to gamma-rays from sodium. Tests of voltage breakdown, mechanical properties, and gas evolution of irradiated samples indicate that a silicone-resin-impregnated mica and glass tape insulation will be satisfactory up to 10^{10} r if it is not in a sealed container

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ELECTRICAL INSULATION used in the Submarine Intermediate Reactor's primary-coolant pump will be subjected to gamma radiation from the liquid-sodium coolant. Thus, development has required study of the effects of high-energy gamma radiation on electrical insulation. This article reviews the important findings.

Pump. Figure 1 shows the electromagnetic pump that will circulate liquid sodium in the reactor's primary coolant circuit (*1-3*). Laminated magnetic structures just above and below a 1-in.-high, 24-in.-thick duct in the pump are energized to move the sodium by the interaction between the magnetic field and a large current that flows across the duct.

Insulation. Because the sodium becomes thermally hot and intensely radioactive during its passage through the reactor, the stator's insulation is subjected both to high temperature and intense gamma radiation. Pump replacement will be difficult and costly once the reactor has been in operation for an appreciable time. Thus it is important to preserve and predict insulation life.

Experience with mica and glass has shown that they possess excellent radiation-resistant qualities. Although the high-temperature requirement dictates an insulation structure with as little organic material as possible, some organic binder must be added to provide necessary mechanical properties. It appeared that a silicone-resin-based varnish would be the most likely candidate for this application. Thus, the major portion of

* Operated by the General Electric Co. for the U. S. Atomic Energy Commission.

study has been on either glass and mica structures impregnated with silicone resin, or on silicone resin films alone.

Sources

Table 1 shows the radiation sources used for these experiments. In the SIR, the insulation will be subjected to primary gammas of 2.76 Mev and 1.38 Mev. Fast neutrons will be present at an intensity 10,000 times lower than the photon flux. Although it was desirable to subject the test specimens to an identical flux, no such source is available. Thus the difficult problem of extrapolation between quite dissimilar sources was faced.

Rate effect. It is customary to assume that the significant parameter is the total energy absorbed by the material as measured by the integrated dose (*7*). For small total dosages and for low rates, this seems true in many cases. However, the equivalence of a dose delivered at a very high rate to the same total dose delivered at, say, one-thousandth of this rate has definitely not been proved. There is evidence that measurably different results can be obtained. However, this study assumes the equivalence of equal doses independent of the rate of accumulation.

Beta-gamma equivalence. Since the primary effect of electromagnetic radiation of the energies under consideration is to produce Compton recoil electrons in the material, a direct equivalence between beta and gamma irradiation is fairly justified. As long as the electrons appear in the material with a given energy, it is not too important how they got there or how they received their energy.

Neutron-gamma equivalence. Preliminary experiments indicated that a combined neutron and gamma flux is much more destructive than the gamma flux alone. This caused reactor irradiations to be of limited utility for these tests.

Dosimetry

Accurate high-level dosimetry was needed to determine accumulated doses. Further, because much of the insulation was (and will be) wrapped around copper and surrounded by iron, it was desirable to determine the actual dose received by the insulation *in situ*.

A ferrous-ferric sulphate solution dosimeter was used most. PVC dye-impregnated films (*8*) were extremely convenient for measurements very near the conductor bars. A scintillation counter also was used (*9*).

Samples

Irradiations were conducted on four kinds of samples: a facsimile stator, voltage-breakdown samples, abrasion bars and resin films.

Figure 2 shows the disassembled stator constructed with a winding that simulates the insulation of the electromagnetic pump. For assembly, the stator was slid into an annular container and a watertight cover was bolted in place. The entire assembly was placed over the Co^{60} source and the winding energized to obtain normal magnetic vibratory forces and copper temperatures.

Voltage-breakdown samples, consisting of narrow bars of glass-cloth laminate impregnated with silicone resin, were wound with nickel foil and covered with a few laps of mica-tape insulation using SR-32 resin as a binder. A number of these specimens were placed in the center of the Co^{60} pit in a gas-tight aluminum container. These were periodically removed and an external aluminum foil electrode wrapped around the outermost insulation. Voltage applied between this and the central foil was used to break down the insulation.

Abrasion bars were pieces of $^3/_8$-in. square aluminum approximately 4 in. long on which mica laid on glass-tape insulation was applied.

Thin resin sheets (10–30 mils thick) also were tested. They were made by casting and curing resin films on metal plates.

Electrical Effects

The quantity of primary interest was the ability of the insulation to withstand applied voltage after a large accumulated radiation dose. Figure 3 shows the results of such a test. Unirradiated samples failed at breakdown voltages between 6.6 and 10.7 kilovolts. This range defines the normal range of variability of the samples. On the basis of three samples broken down after 2.4×10^6-r/hr irradiation, no reduction in voltage breakdown was detected up to 1.2×10^{10} r. This indicates that the insulation will be satisfactory for the SIR pump.

The liberation of large numbers of electrons by gamma absorption conceivably could provide initiators for an avalanche process. Breakdown then would occur at lower applied fields (*10–12*). Figure 4 shows 60-cycle, short-time voltage breakdown on Formex-insulated wire (Formex used for experimental convenience) at room temperature. The fact that voltage breakdown for irradiated specimens was substantially the same as that for specimens not under irradiation indicates that electron-liberation has a very minor effect for the case of interest.

A further experiment to shed some light on this process was carried out using the external electron beam

TABLE 1—Source Characteristics

Source	*Optimum sample size*	*Approximate dose rate*	*Ambient*	
			Normal	*Changes*
GE Res. Lab. extern. beam	≤2 in. dia., 0.040 in. thick ($\rho \sim 1$)	10^9 r/hr (β)*	20° C air	possible
Oak Ridge reactor	6 in. long, $3^1/_2$ in. sq. or 2 in. dia.	10^6 r/hr (γ) 10^{12} n/cm²/sec†	20° C air	difficult
Brookhaven reactor	6 in. long, $3^1/_2$ in. sq. or 2 in. dia.	5×10^6 r/hr (γ) 5×10^{12} n/cm²/sec†	160–180° C air	difficult
HEW disch. fuel elem.	8 in. long, $1^5/_8$ in. dia.	$1–2 \times 10^5$ r/hr‡	20° C water	practical
MTR disch. fuel elem. (*5*)	10 in. long, 3 in. sq.	8×10^6 r/hr‡	20° C water	practical
KAPL 3,000-c Co^{60} source (*6*)	6 in. long, $1^1/_4$ in. dia., or annular volume	2×10^6 r/hr§ 0.5×10^6 r/hr	20° C water	practical

* 0.8-Mev peak sinusoid. † Fission spectrum. ‡ Fission-product spectrum. § 1.33 and 1.17 Mev.

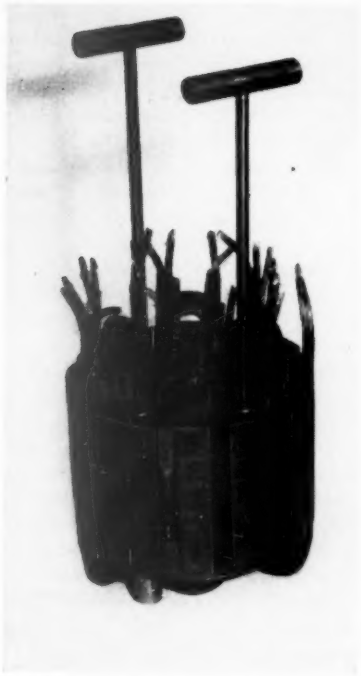

FIG. 2. Test stator whose winding simulates electromagnetic pump stator

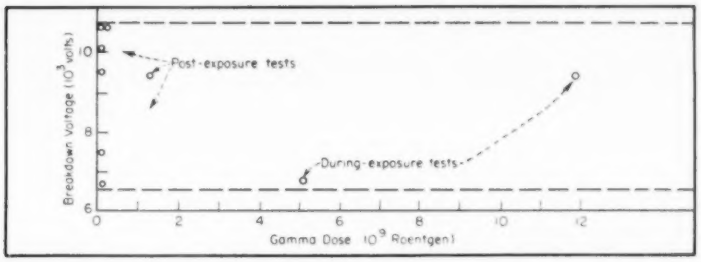

FIG. 3. Short-time breakdown voltage as function of accumulated radiation dose for glass-backed mica tape impregnated with SR-32 resin

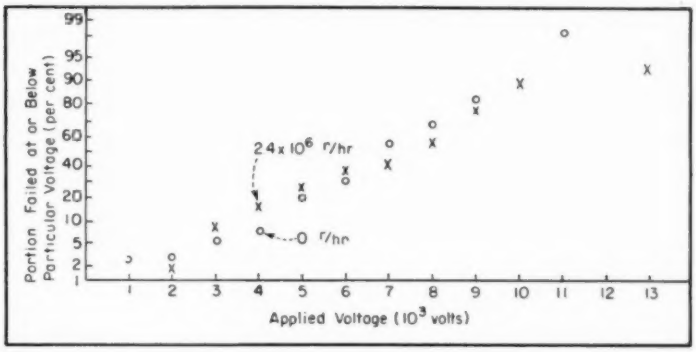

FIG. 4. Short-time, 60-cycle breakdown voltage on irradiated and unirradiated Formex insulated wire at 20° C

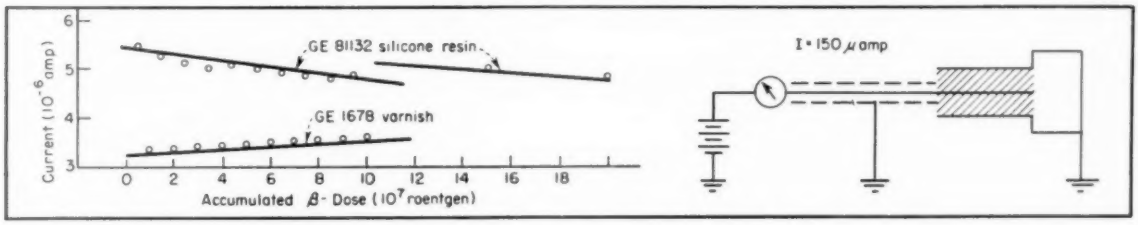

FIG. 5. Current passing through resin films as function of accumulated radiation dose

facility. Two thin films of resin were contained between very thin outer aluminum foils. As shown in Fig. 5, a central foil was maintained at a positive potential and the current flow from the central foil to ground measured on a microammeter. A certain number of the incident electrons terminated on the central foil and thus produced a static current in the circuit and decreased the total sensitivity of the experiment. If the insulation had changed from an essentially nonconducting to a conducting state under the influence of the radiation field, there would have been an increase in current as irradiation continued. Such an increase was not observed, and it was concluded that the specific resistivity of the material did not undergo a catastrophic decrease for irradiations up to 2×10^8 r. The silicone-resin curve is broken because a second sample of different thickness was used.

These results were corroborated by measurements on the stator windings. Resistance and power factor measurements on unirradiated insulation and on the stator after 6×10^8 r are within the normal range and actually show a slight improvement after irradiation. This is undoubtedly due to the evolution of water and solvent vapors and to additional polymerization.

Although power factor measurements have been used extensively to determine changes in molecular structure (*13*), our extensive measurements from low audio frequencies to the megacycle range on thin films of resin in various stages of irradiation showed no consistent variations. In spite of its ease of application and nondestructive nature, this technique was not fruitful for the resins of major interest at this time.

Mechanical Properties

The mechanical properties of insulation are next in importance to the electrical properties. The evaluation of which mechanical properties are necessary, and to what degree, is a question that has never been settled on a quantitative basis.

An empirical method of evaluating comparable kinds of insulation is provided by an "abrasion tester" (*14–16*). The total number of turns required for a striking and rubbing motion to cause failure is a measure of the abrasion resistance of the insulation. Figure 6 gives results of tests on specimens irradiated in the Oak Ridge and Brookhaven reactors. The general conclu-

TABLE 2—Summary of Gas Evolution from Various Samples

Quantity	*Sample*		
	Dielectric breakdown	*Cable coil*	*Stator*
Resin wt. (gm)	10	4	89
Added heat cure before irradiation	None	None	24 days; 140° C
Comparison with pump winding	Similar	Very diff.	Nearly ident.
Radiation from	Co^{60}	HEW slugs	Co^{60}
Irradiation (equiv. avg. pump days)	170	400	63
Irrad. temp. (°C)	25	25	45
Total gas evolved (cm^3)	54	8.7	982
Gas factor (cm^3/[eq. day × gm])	0.033	0.49	0.16
Gas retention by insul. structure	High	Negligible	Moderate
Gas analysis (CH_4 = 1)			
CO_2	Trace	0.46	2.5
H_2	1.23	None	4.4
C_6H_6	None	None	1.1
Xylene	0.19	None	None
O_2	0.1	Trace	None
Major uncertainties	Degree of cure	Mass spectrom. anal., rad. level	Corr. for leak, gassing by top gask. in stator can

TABLE 3—Gases Evolved* from Impregnated† Glass Tape During Gamma Irradiation‡

		H_2(%)		CH_4(%)		N_2 or CO(%)	C_6H_6(%)	
Catalyzed	*Sized*	*In N_2*	*In vac.*	*In N_2*	*In vac.*	*In vac.*	*In N_2*	*In vac.*
Yes	Yes	49.5	38.9	39.3	40.6	2.7	11.0	15.9
Yes	No	51.8	42.0	41.3	41.8	2.0	6.9	12.1
No	No	17.5	10.4	32.9	13.6	3.8	49.6	70.3
No	Yes	15.9	10.7	30.4	19.1	4.9	53.6	65.3

* Approximately 0.6 cm^3 gas evolved per gm of resin, both in nitrogen and *in vacuo*. Nitrogen pressure over samples sealed in N_2 = 150 mm.
† With 3.25 wt. % zinc octoate catalyzed SR-32.
‡ 4×10^8 r accumulated dose from discharged MTR elements.

TABLE 4—Gas Evolution from 10^{-3} mm Films of SR-32 During Pyrolysis

Time	*Temp. (°C)*	*Evolution rate (10^{-6} liter/min)*	*Composition*
15 min	90	0.5	Methyl trimer, tetramethylsilane and low mol. wt. silanes
30 min	95		
40 min	135	0.25	95% C_6H_6, 4% H_2O, 1% trimer
70 hr	135	0.0042	95% C_6H_6, 4% trimer
3 hr	150		C_6H_6, H_2O, cyclic trimer, tetramers
16 hr	220		50% C_6H_6 20% hexamethyltricyclosilane

sions are that mechanical properties of silicone-resin-and-mica-tape insulation are not particularly affected by 30-day irradiation at 160–180° C, but 60-day irradiation at this temperature greatly reduces mechanical strength.

It is generally felt that insulation should withstand thousands of turns before failure and any that withstand only a few hundred turns will not be satisfactory. The significance of loss of abrasion resistance as relates to life of the insulation *after* the insulation has been installed will depend to a very large degree on the individual piece of equipment. Equipment in which insulation has reached a condition that would give a very low abrasion-resistance measurement can give long reliable service under severe conditions. Thus, this change in abrasion resistance should not be interpreted in terms of proportional decrease in insulation life.

The behavior of the phosphoasbestos paper (shown as a range of values) is extremely interesting. This material, initially poor, apparently suffers no further deterioration and in its final condition is apparently superior to the silicone resin and mica tape.

The entirely empirical results of the abrasion tester and the inability of a device of this kind to evaluate the "weak link" (i.e., the resin) in the insulation structure has led to an investigation now in progress. It is believed that more useful information can be derived from study of penetration times of styli in thin films of resin irradiated by the external electron beam.

Gas Evolution

Initially it was believed that considerable insight into mechanisms of decomposition could be obtained by study of components present in the resin off-gas. Table 2 summarizes the first data obtained. Two facts were evident: 1, evolution of gas was of sufficient magnitude to cause concern in a sealed container; 2, the "signature" of decomposition products was substantially different from one sample to the next. While some small differences in degree were anticipated, the differences in kind that were observed seemed beyond any reasonable limit.

A systematic approach to the problem was taken by attempting to isolate significant variables as shown in Table 3. One of the presumed variables is the catalyst, in this case about $3\frac{1}{4}$ weight % of zinc octoate added during

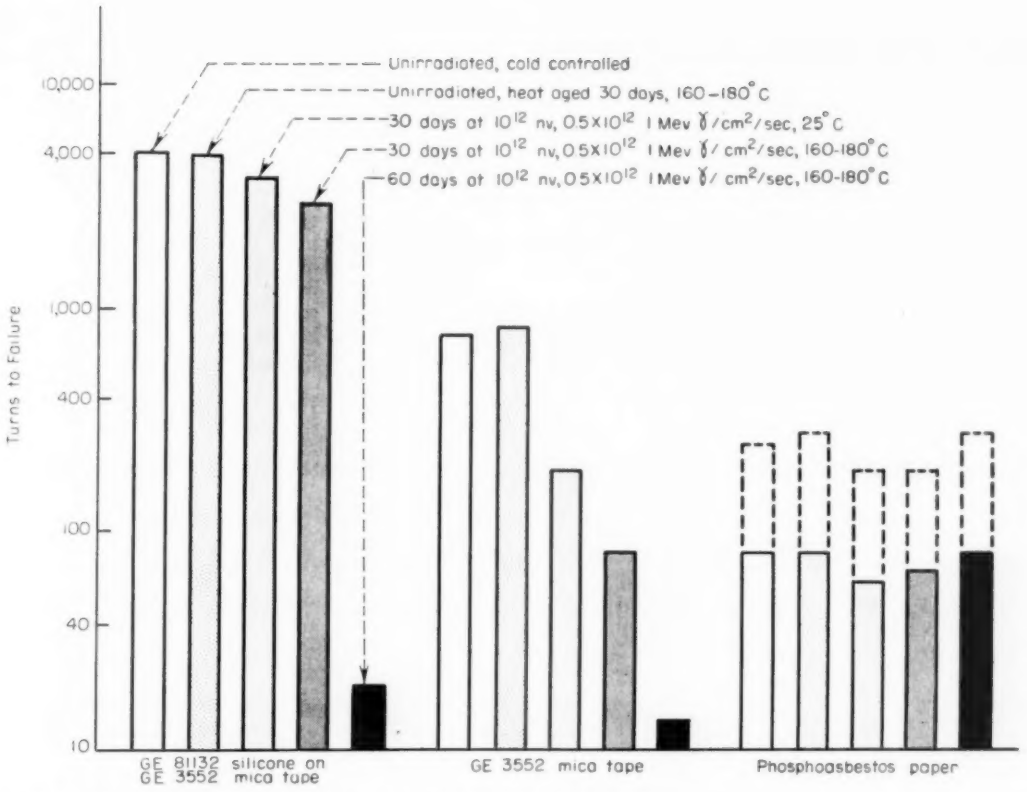
Unirradiated, cold controlled
Unirradiated, heat aged 30 days, 160–180° C
30 days at 10^12 nv, 0.5×10^12 1 Mev γ/cm²/sec, 25° C
30 days at 10^12 nv, 0.5×10^12 1 Mev γ/cm²/sec, 160-180° C
60 days at 10^12 nv, 0.5×10^12 1 Mev γ/cm²/sec, 160-180° C
Turns to Failure
10,000
4,000
1,000
400
100
40
10
GE 81132 silicone on GE 3552 mica tape
GE 3552 mica tape
Phosphoasbestos paper

FIG. 6. Effect of radiation on abrasion resistance of 8-mil thick insulation tapes

final formulation of the resin to "body" it. As the resin ages, this zinc octoate will break down providing some free zinc and octoic acid. Thus the composition of the resin was to some extent a function of time, and it was expected that the catalyst might be particularly vulnerable to disintegration under irradiation. Another variable related to the sizing already on the glass tape before impregnation with the resin.

Examination of the data shows no substantial difference between the sized and unsized samples. In one instance, comparison of the nitrogen and vacuum atmosphere results shows a discrepancy that seems to be considerably beyond experimental error; in all other cases the agreement between the nitrogen and vacuum atmosphere is good. There is a marked difference between the catalyzed and uncatalyzed results. These results were obtained at a time when the total gas pressure could not be measured, and it is not possible to tell whether the results differ because the percentage composition differs, or whether the catalyzed resin simply produces much more hydrogen.

Whatever the differences due to the variations exhibited in Table 3 the process is substantially different than that which the resin experiences in pyrolysis. Table 4 follows the decomposition of an extremely thin film of resin deposited on the inside of a quartz bulb (*17*, *18*). Extensive low-temperature degassing was undertaken prior to the pyrolysis. The molecular fragments observed as a function of time and temperature are entirely different from those observed as a consequence of irradiation. It seems reasonable to conclude that the thermal and radiation degradation processes are essentially different in detail.

* * *

This article is based on a paper presented at the Radiation Damage Conference, Oak Ridge National Laboratory, March 24, 1953.

It is a pleasure to acknowledge the assistance of numerous associates. S. S. Jones was responsible for correctness of dosimetry and for procurement and many of the details of the Co^{60} pit; H. Rudoff, E. L. Mincher, J. W. Ryan, and L. F. Wardell, of the G. E. General Engineering Laboratory, carried out many of the tests and prepared and analyzed samples; C. Doyle prepared the SR-32 resin; W. B. Lewis at MTR, W. Powell at BNL, O. Sisman and C. D. Bopp at ORNL assisted in the use of facilities at their sites; P. H. Klein assisted in the gas analysis problem; H. Mattraw performed numerous mass spectrographic analyses; D. H. Ware and R. Rhudy of GE's Small and Medium Motor Department had samples prepared according to factory procedures; E. Flynn and K. Mathes contributed to numerous discussions relating to properties of commercial insulations; A. Pletenik took extended data relating to power factor and the penetration of irradiated plastic films by means of styli; E. J. Lawton of GE's Research Laboratory irradiated resin samples with the 0.8-Mev peak external electron beam facility; R. Dewes of GE's General Engineering Laboratory designed and constructed equipment; C. S. Hofmann and R. Washburn helped build the penetration device, and P. Zemany supplied pyrolysis data.

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RADIATION STERILIZATION IX

Radiological Safety in Cathode-Ray Sterilization

Conservative estimates and assumptions based on the limited data now available are used in calculating shielding requirements for a hypothetical 3-Mev sterilization unit producing 12 kw. A broad safety program is set forth to reinforce personnel protection afforded by such shielding of the installation

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AN IMPORTANT FACTOR to be considered in any proposed installation for radiation sterilization of food and drugs is protection of personnel.

This article considers the factors necessary in establishing an adequate radiological safety program for a sterilization installation. As shielding is a major problem, an effort has been made to present simplified material for estimating shielding requirements for electron accelerating potentials up to about 4 Mev (million electron volts). Since experimental data are not yet available for cathode-ray accelerators in the 2.5 to 4 Mev energy range, the assumptions and methods presented are in the direction of over-protection.

Cathode Rays

Cathode rays consist of a beam of negatively charged electrons accelerated by an electrostatic or electromagnetic field. The electrons are physically identical to negatively charged beta rays emitted by radioisotopes. But, when accelerated by a constant potential, cathode rays can be made monoenergetic.

Cathode rays passing through matter give up energy through excitation, ionization, and radiation processes. In the radiation process the electron energy loss is converted into production of X-rays or bremsstrahlung (*1*).

Optimum conditions for cathode-ray sterilization have been discussed recently (*2*). The density and thickness of the product to be sterilized and its container impose a lower limit on the accelerating voltage.

Energetic electrons are completely stopped by relatively small thicknesses of material as shown in Fig. 1 (*3*), and shielding of the sterilization accelerator would be comparatively light weight were it not for the bremsstrahlung produced when the cathode rays dissipate their energy in the food product, its container, and surrounding materials.

Another problem is to prevent fast electrons from escaping through apertures that may be necessary in a shielded enclosure. This problem is caused by the extensive scattering that occurs as electrons pass through air or strike solid materials. Trump and Van de Graaff (*4*) have investigated the scattering of high-energy electrons incident on thick targets. It was found that the ratio of the number of secondary to the number of primary electrons diminishes with increasing primary energy and increases with the atomic number of the target material. A value of approximately 0.2 is reported in the same paper for the ratio of secondary to primary for 340-kv electrons incident on aluminum.

X-ray Production

Considering the direction of a beam of cathode rays as zero degrees, X-rays are produced at the target material in all directions, with the maximum intensity in the forward direction, 0 deg.

Experimental data presented by Buechner *et al.* (*5*) is extremely useful in determining thick-target X-ray production for monoenergetic electrons. Figure 2 shows Buechner's data, plotted in convenient form, and extrapolated to about 4 Mev. The curves show X-ray intensity at 1 meter in the forward direction per milliampere of beam current for beryllium, aluminum, silver, and gold targets. The extrapolation beyond 2 Mev appears acceptable on the basis of recent measurements at MIT, where it was found that thick-target X-ray production in the forward direction for monoenergetic cathode rays from 1 to 3 Mev is roughly proportional to $E^{3.4}$, where E is the accelerating potential (*6*).

Buechner's paper also presents curves that give approximate values of thick-target X-ray intensity at various angles from the direction of the cathode rays as a function of electron energy. The data are plotted in Fig. 3. Once again, extrapolations have been made.

X-ray intensity at any angle does not appear to be a simple function of either

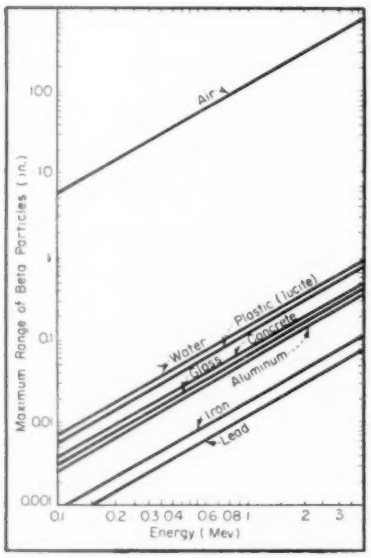

FIG. 1. Maximum range of electrons as a function of energy (3)

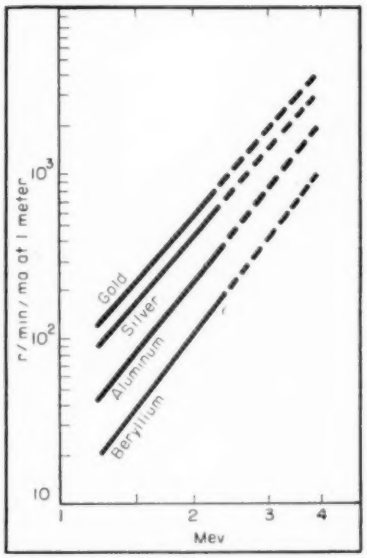

FIG. 2. X-ray intensity in the forward direction as a function of voltage

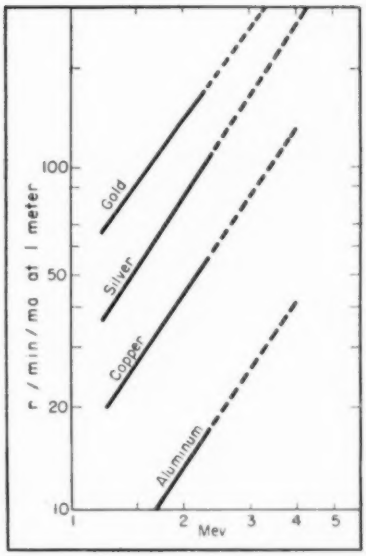

FIG. 3. X-ray intensity at an angle of about 100 deg as a function of voltage

atomic number of target material or of the energy of the bombarding electron. However, total X-ray production, integrated over all angles, is closely linear with atomic number in the energy range being considered (*5*). It is possible, therefore, to minimize X-ray production at the target area by using low-atomic-number materials on surfaces that will be struck by the cathode rays. Lead shielding, for example, should be lined with aluminum of thickness greater than the maximum range of the electrons. It should also be feasible to use low-atomic-number materials for the food conveyer system.

Although the use of beryllium would minimize X-ray production, its low photoneutron threshold (at 1.67 Mev) makes this advantage of questionable value, since neutrons can be produced by the interaction of above-threshold X-rays with beryllium. This factor would have to be considered with respect to neutron-induced radioactivity and also neutron shielding.

The contribution of scattered X-radiation is insignificant compared to the primary X-ray intensities produced at 90 to 270 deg. For energies up to 2 Mev and at 90 deg from the direction of the primary beam, NBS Handbook 41 suggests assuming a scattered intensity at 1 meter from the scattering medium of 0.1% of the intensity of the primary X-ray beam (*7*). It is also suggested that 0.5-Mev X-ray absorption curves be used for scattered radiation from primary photons having energies above 0.5 Mev. These approximations will be used in a later section to obtain a conservative estimate of shielding requirements.

X-rays produced by monoenergetic and heterogeneous electrons have a continuous spectrum of energies with the maximum energy equal to the maximum accelerating potential. The term quality is used to describe the approximate characterization of the X-radiation with respect to its penetrating ability. Quality is often expressed in terms of the effective wave length or effective energy of the radiation.

In X-ray shielding calculations, the maximum energy of the incident electrons can be used as a very conservative estimate of the effective energy of the X-rays. There is, however, experimental evidence in the 2 to 10 Mev range to justify using the approximation that the effective energy of X-rays produced by constant-potential and pulsed electron accelerators is equal to about one-half the value of the maximum potential applied to the accelerator (*8, 9*).

The dependence of X-ray quality on the angle of production from the forward direction has been investigated for radiation produced by 1.09 to 1.63 Mev electrons striking a thick gold target (*10*). For these energies it is found that the mass absorption coefficient in lead for X-rays produced at 90 deg differs by less than 20% from the value at 0 deg.

Shielding Aspects

The familiar exponential absorption formula $I = I_0 e^{-\mu t}$ is simple to apply when monoenergetic photons are being considered. Tables of the linear absorption coefficient, μ, versus energy for various elements are readily available (*11*). It is expedient, and usually more accurate, to refer to experimental absorption curves if they are available in the desired energy range. Experimental lead and concrete transmission curves are numerous in the literature for photon energies up to about 2 Mev (*8*), but not for 2 to 10 Mev.

Calculated transmission and absorption curves are in the literature that have been obtained by substituting appropriate values of μ in the exponential absorption formula. A convenient graph is shown in Fig. 4, where the thicknesses of various materials to reduce the X-ray intensity by a factor of 10 (tenth-value layer, TVL) is plotted as a function of energy (*3*).

Tenth-value layers can be related to half-value layers (HVL) as follows: Writing the exponential absorption formula in logarithmic form, $\text{TVL} = \ln (10/1)/\mu = 2.30/\mu$. Similarly, $\text{HVL} = 0.693/\mu \simeq 0.3$ TVL.

Two basic considerations in shielding

To accommodate existing facilities of a food packaging plant, it is necessary to install a horizontally aligned accelerator at a ground-floor location of a conveyer system. The sterilization requirements are such that a 4-milliampere beam of 3-Mev cathode rays is necessary. A layout of the 12-kw accelerator and its shielding is shown in Fig. 5.

Sample Calculations

1. Aluminum lining thickness. To conserve space, lead shielding will be used for the primary radiation barrier. From Fig. 1, the maximum range of 3-Mev electrons in aluminum is approximately $\frac{1}{4}$ in. An aluminum lining of this thickness on all surfaces surrounding the sterilization area will minimize X-ray production.

Considerable heat will be generated by electron absorption for a stationary target in the path of the cathode-ray beam. Cooling of the primary barrier surface can be accomplished by water coils imbedded in an aluminum block.

2. X-ray intensities. With the assumption that the average atomic number of the products to be sterilized is less than that of aluminum, the anticipated maximum X-ray intensities for 3-Mev monoenergetic cathode rays are:

Forward direction. As shown by the aluminum curve in Fig. 2, a 1-ma beam produces approximately 800 r/min at 1 meter, or approximately 3,200 r/min at 1 meter for 4 ma.

In all other directions. It is assumed that the intensity of the X-rays produced at any angle between 90 and 270 deg is approximately equal to the intensity at 100 deg. As shown by the aluminum curve in Fig. 3, a 1-ma beam produces approximately 25 r/min at 1 meter, or about 100 r/min at 1 meter for 4 ma.

It is assumed that the effective energy of the X-rays produced in all directions from the target is approximately equal to one-half the maximum accelerating potential. Therefore, in this sample problem the effective energy of the X-rays is assumed to be 1.5 Mev.

3. Shielding, primary barrier. The level of 3,200 r/min at 1 meter is to be reduced by a factor of (0.1 mr/min)/$(3.2 \times 10^6$ mr/min) = $1/(3.2 \times 10^7)$ or approximately 7 TVL and 2 HVL. From Fig. 4, a TVL for 1.5-Mev photons is about 1.6 in. of lead. Thus 7 TVL = $7 \times 1.6 = 11.2$ in., and 2 HVL = $2 \times (0.3 \times 1.6) = 1.0$ in. Therefore, total thickness is about 12 in. of lead.

4. Shielding, accelerator tube extension. From 2, the intensity is 100 r/min at 1 meter. Then, by inverse square law, the intensity at 2 meters is 25 r/min, and the reduction factor required = $1/(2.5 \times 10^3)$ or approximately 5 TVL and 1 HVL. About 1 TVL and 1 HVL will be provided by the accelerator's concrete enclosure, which is discussed later. Therefore, the lead thickness required is 4×1.6 or about 6 in.

5. Shielding, maze walls. A maze is used to shield the conveyer system openings in the lead shielding. The requirements for maze wall section 1 are the same as in the preceding section, and thickness = 6 in. of lead.

The thickness required for the maze walls shown as sections 2 (Fig. 5) is determined by estimating the X-ray scattering from lead sections 1. This will be in the order of 0.1% at 1 meter of the 100 r/min primary radiation from the target area. The scattered X-radiation will be assumed to have an effective energy of 0.5 Mev, and $0.1\% \times 100$ r/min = 100 mr/min at 1 meter. Therefore, reduction required in TVL = 3. From Fig. 4, at 0.5 Mev a TVL = 0.3 in. of lead. Therefore, the thickness required for sections 2 equals approximately 1 in. of lead.

6. Shielding, in 180-deg direction. The 180-deg X-radiation produced at the target area will be collimated by the shielding around the accelerator tube extension to a fairly small cross sectional area. The length of the accelerator shell is given as 4 meters and the target area is 1 meter below the shell base.

The anticipated intensity of the collimated radiation at the top of the accelerator, neglecting absorption by the shell wall and interior parts, is 100 r/min $\times 5^{-2} = 4$ r/min. To reduce this to 0.1 mr/min requires 4 TVL and 2 HVL; and 4 TVL = about 6 in. of lead, 2 HVL = 1.0 in. of lead or about 2(0.3 × 7.5 in.) = 4.5 in. of concrete.

The 4 TVL of lead is shown as shielding section 5 in Fig. 5. The 2 HVL will be provided by the concrete door.

7. Accelerator shield enclosure. Shielding will be required all around the accelerator shell, since scattering from the 180-deg primary radiation will occur along the axial length of the accelerator tube. In addition, there will be a small contribution of X-ray production by defocussed electrons striking the inside of the accelerator tube.

A conservative estimate of the X-radiation emitted perpendicular to the axial length of the shell is made by assuming 0.1% scattering at 1 meter of the 180-deg radiation, with a scattered radiation effective energy of 0.5 Mev.

A concrete enclosure seems desirable, with adequate work space around the accelerator and its support for repairs. A caster-supported door at the back end is specified to allow removal of the shell.

The maximum anticipated intensity at about 1 meter from the shell side is (neglecting shell absorption) 100 r/min $\times 0.1\% \times 2^{-2} = 25$ mr/min. A reduction to approximately 0.1 mr/min (for 0.5-Mev photons) requires 2 TVL and 1 HVL, and 2 TVL = 2×5 in. = 10.0 in. of concrete, 1 HVL = 5 in. $\times 0.3 = 1.5$ in. of concrete. The total is approximately 12 in. of concrete.

This thickness is required for the enclosure shield sides near the accelerator shell base. It is practical to use the same thickness for the entire concrete enclosure except for the door.

8. Conveyer aperture. The majority of the electrons in the cathode-ray beam can be expected to dissipate their energy in the target or food sterilization area. However, a small but significant fraction will undergo multiple scattering collisions and will emerge from the lead maze apertures with a continuous distribution of energies up to almost 3 Mev. Since the maximum range of 3-Mev electrons is about 12 meters in air (Fig. 1), these electrons must be considered when designing apertures in the concrete enclosure for the conveyer system.

One solution would be to use an electromagnetic deflection apparatus to prevent the electrons from escaping the lead maze.

Another solution is to utilize an extended maze system and depend on multiple scattering losses to reduce the electron flux at the conveyer aperture to a permissible exposure value. See Fig. 5.

With the accelerator operating at 4 ma, the approximate number of electrons emerging from the tube extension is 4 ma $\times$ (10^{-3} coulombs/sec)/ma $\times$ 1/(1.6×10^{-19} coulombs/electron) = 2.5×10^{16} electrons/sec.

For the most advantageous scattering path through the maze, it appears that an electron can emerge or escape from the concrete aperture after undergoing a minimum of about 10 surface scattering collisions. If it is assumed that 20% of the electrons striking a surface are scattered and if about half of these travel in the "escape" direction, then the factor for reduction in electron flux per surface scattering encounter is about $\frac{1}{10}$.

Using this factor and assuming 10 scattering events, the number of electrons emerging from the aperture in the concrete enclosure is 2.5×10^6 electrons/sec. The cross sectional area of the aperture is expected to be about 1,000 cm². The electron flux emerging from the aperture is thus 25×10^2 electrons/sec/cm². The flux of electrons equivalent to 6.25 mr/hr of X-rays is about 40 electrons/sec/cm² for 2-Mev electrons (*13*).

An unsafe radiation level is indicated by the preceding calculation. However, it is to be expected that a heterogeneous flux of electrons emerging from an aperture of 1,000 cm² to an area of relatively infinite size will be "diluted" by air scattering to a much smaller flux value in terms of the number of electrons/sec/cm². It is not unreasonable to expect a factor of at least 10^{-2} reduction in electron flux about a meter away from the concrete aperture. Another large reduction factor is indicated because of the use, in the calculations, of the minimum number instead of the average number of scattering events.

If, in the initial radiation survey, a radiation level is found that is less than about 10^3 times the permissible flux, the electrons can be shielded effectively by installing a 0.5-in. sheet of Lucite opposite the conveyer opening.

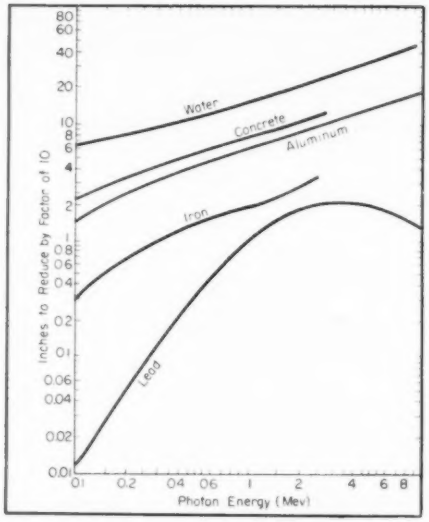

FIG. 4. Tenth-value layers for various materials as a function of X- or gamma-ray energy (3)

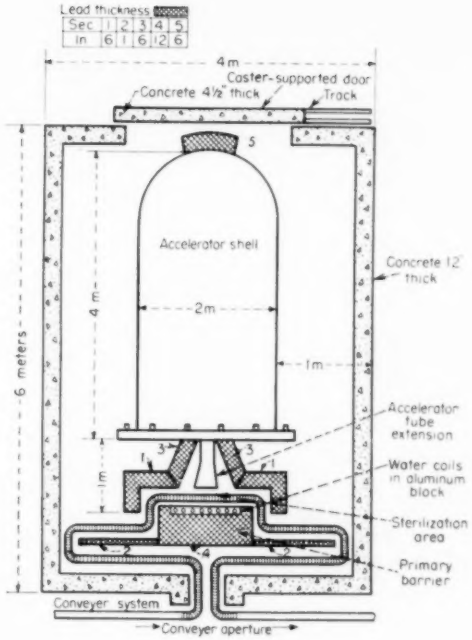

FIG. 5. (RIGHT) Calculated shielding for a 12-kw sterilization unit producing 3-Mev cathode rays

design serve to reduce construction costs:

1. Install shielding as close as possible to the source of radiation.

2. Utilize natural shielding when it is possible. For example, by installing an accelerator below ground level, or in the side of a hill, the earth can be used as an effective shield.

Permissible Exposure

As a working guide, the International Commission on Radiological Protection recommends a maximum permissible whole-body exposure to X- or gamma-rays (up to 3 Mev) of 300 mr/week measured in air (*12*).

For a 48-hr work-week, 300 mr/week is equivalent to 6.25 mr/hr or approximately 0.1 mr/min. The permissible dose rate of 0.1 mr/min is used in shielding calculations on page 56, with the understanding that the conservative assumptions employed introduce a safety factor of at least two for the anticipated radiation level outside the shield.

Safety Considerations

To provide adequate protection for the operators of the sterilization unit and for other personnel in the area, a formal radiological safety program is required. It should include such essential features as:

Radiation survey. Measurements should be made, with the accelerator operating at a maximum power, of the radiation levels in all areas adjacent to the unit where personnel can be located.

Continuous radiation monitoring. Certain operational difficulties can result in the cathode-ray beam striking the inside of the accelerator tube walls. This presents two problems: increased radiation around the accelerator shell, and inadequate doses to the sterilization area.

A reasonable precaution would be to install ionization-chamber radiation monitors with meter outputs fed to recorders or alarm systems. For example, an area monitor could be located permanently at the side of the concrete enclosure. Its accompanying alarm system would be preset so that an undesirable increase in radiation would sound an alarm and/or de-energize the accelerator.

Monitoring of the sterilization dose could be accomplished by means of a small ionization chamber or a Faraday cage detector located inside the cathode-ray-beam target area.

Personnel monitoring. To assure that personnel exposure stays within permissible limits and to provide a continuous record of individual exposure, all workers in the radiation area should be provided with film badge service.

Safety interlocks. Additional factors of safety can be provided by the use of interlocks and warning lights.

Medical examinations. It is generally agreed that workers who may be exposed to significant amounts of radiation should be given pre-employment physicals. For anticipated low-level exposure, the medical program may require a series of three blood tests, taken at 1-wk intervals, to establish an individual's "base line" count.

Personnel training. Indoctrination in the radiological safety program for the workers plus its implementation should be assigned to a qualified member of the supervisory staff.

* * *

The author wishes to acknowledge the helpful suggestions of Mr. Kenneth Wright and the able assistance of Miss Helen Watson in preparing the manuscript.

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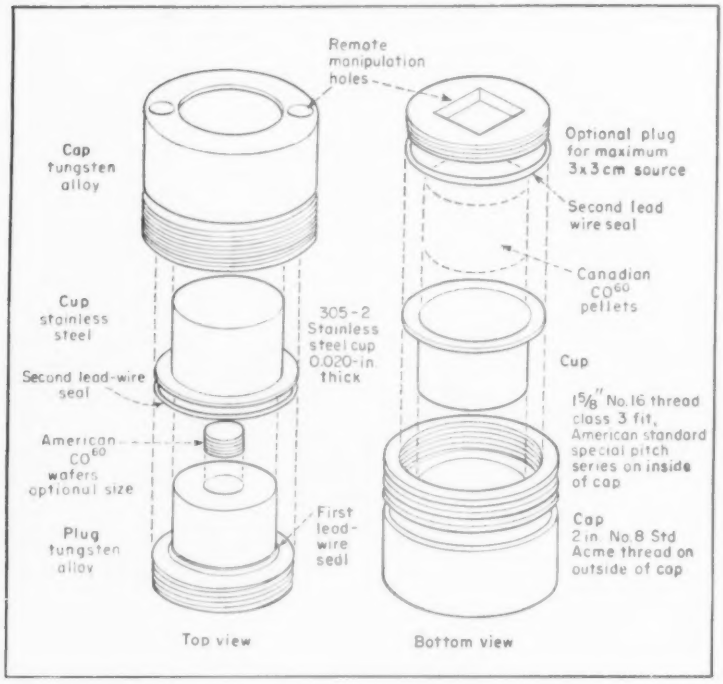
Remote manipulation holes
Cap tungsten alloy
Optional plug for maximum 3x3 cm source
Second lead wire seal
Canadian CO^{60} pellets
Cup stainless steel
305-2 Stainless steel cup 0.020-in. thick
Cup
Second lead-wire seal
$1\frac{5}{8}$" No. 16 thread class 3 fit, American standard special pitch series on inside of cap
American CO^{60} wafers optional size
First lead-wire seal
Plug tungsten alloy
Cap 2 in. No. 8 Std Acme thread on outside of cap
Top view
Bottom view

STANDARD CAPSULE for Co^{60} hectocurie and kilocurie teletherapy units. Maximum size of capsule is 2 in. in diameter, $1\frac{7}{8}$ in. in length

Standardized Co^{60} Source Capsule for Teletherapy

By MARSHALL BRUCER
Oak Ridge Institute of Nuclear Studies
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Representatives of equipment manufacturers, the Atomic Energy Commission, Atomic Energy of Canada, Ltd., and Oak Ridge National Laboratory have agreed upon a standard source capsule for Co^{60} teletherapy units.

Several factors make standardization attractive at the present time. First, the technological complexity of Co^{60} production has caused AEC and Atomic Energy of Canada to choose a limited variety of sizes. With these standard sizes, it is possible to devise high-activity sources of almost any required number of curies.

Second, assembling small pieces of Co^{60} into a teletherapy source requires specialized tools and equipment. An accepted standard for safe encapsulation of Co^{60} sources has been formulated by subcommittee 9 of the National Committee on Radiation Protection; it will be published shortly in NBS Handbook 54.

Third, while decay limits length of use of a source in a particular teletherapy unit, the source may still contain a large number of curies. One solution is reirradiation of the partially decayed source, which the Canadians have indicated is feasible. AEC's position is that it is cheaper to start with inactive cobalt for each source.

Another solution is that sources no longer useful in kilocurie machines can be used in units needing lower activities. The Teletherapy Evaluation Board has developed a machine designed for a maximum of 600 curies; a 200-curie machine is planned; and a few machines in the 50 to 100 curie range have been constructed. With a standardized source capsule, unloading and loading a capsule would be eliminated and transfer would involve no more than a handling charge.

Early standardization, however, might easily be outmoded. Industry representatives have agreed to meet about twice each year to discuss current development problems of teletherapy machines. Late in 1955, the standardized source capsule will be reviewed by the entire industry.

Standard Capsule Design

The now accepted standard source capsule is shown in the illustration on this page. Detailed drawings of it are available from Medical Division, ORINS.

This standard capsule is designed to meet the following requirements:

1. Size of source. The capsule is adaptable to all projected source sizes of Canada and the U. S.

2. Activity of source. With presently obtainable 50 curies/gm specific activity, the capsule can accommodate more than 4,000 curies of Co^{60}.

3. Capsule material. Since the capsule is in the most economical position for shielding, it must be part of the primary radiation shield. Tungsten alloy completely surrounds the source except in the direction of the primary beam. A wide forward shoulder gives maximum shielding immediately adjacent to the primary beam; all screw threads are at the rear in less critical areas.

4. Airtight seals. A positive double hermetic seal is necessary to prevent leakage of particles of Co^{60}. The present design has two lead-wire seals. The larger primary seal is partially pressure-welded into position by an incomplete seating of the plug to allow preassembly of cap and cup. The smaller lead wire is prefitted to the plug.

In final assembly the two preassembled pieces are screwed into place under high torque; cold flow of lead into the screw threads and between cap and cup forms a continuous airtight seal.

It will be difficult to break the seal. If reloading is necessary, it will be possible to cut off the top window of the stainless-steel cup with special tools.

5. Loading of capsule. This design

is suitable for both Canadian and U. S. methods of loading. Only one set of jigs will be necessary for all sources.

6. Manipulation of capsule. Only one part need be handled by remote control equipment, the solid outer cap.

7. Radiation window. The present design uses an 0.02-in. cover of stainless steel. This is regarded as the best compromise between sufficient strength and minimal attenuation.

8. Emplacement of capsule. The design allows for several methods of emplacement in teletherapy units; mechanical pressure, screw threads, a simple shelf arrangement, or use of the source as a free-floating bearing.

* * *

Criticisms of the present design and suggestions for its improvement will be welcomed. The author is acting only as a reporter of conclusions reached through the combined efforts of representatives of many organizations.

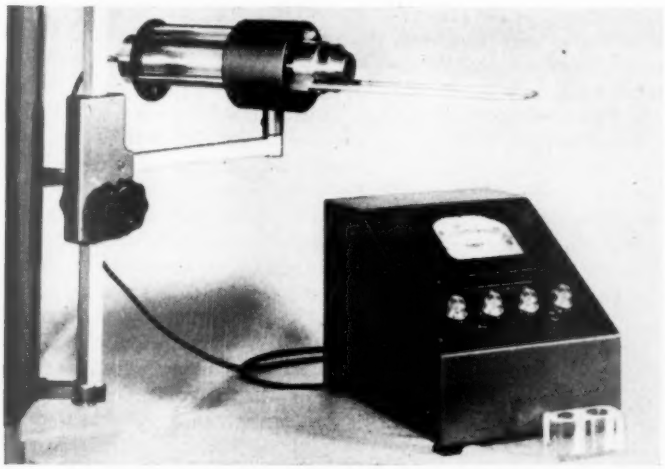

FIG. 1. NaI scintillation counter; spacing bar maintains constant source-to-detector distance

FIG. 2. Multiple G-M tube counter and milk container for I^{131} urinary excretion

Simplified Method for Determining Thyroid Function with Radioiodine

By J. W. LEWIS
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Colorado Springs, Colo.

In the past three years, we have investigated over 1,800 patients for the presence of thyroid disease by the use of radioiodine. We have undertaken this study from two angles: One, the efficiency of the examination, and two, the ease with which the examination can be done. These methods have been correlated with the conventional basal metabolic rate and with the clinical impressions of the department of metabolic diseases.

The use of radioactive iodine in the diagnosis of thyroid disorders has become an accepted procedure (*1–4*), but the usual methods are somewhat complicated and time consuming. To simplify the procedure greatly and eliminate calculations that complicate uptake and urinary excretion studies, two instruments were designed by Dr. John Victoreen. One is a scintillation counter (Fig. 1), which is used to determine the radioiodine uptake of the thyroid gland. In this instrument the pulses are amplified, discriminated, integrated and then indicated on a vacuum-tube voltmeter circuit arranged to read directly in percentages. This instrument utilizes a $1\frac{1}{2}$-in. sodium iodide crystal shielded by $1\frac{3}{4}$ in. of lead and has a collimating beam that covers a 5-in. diameter at 14 in. A 14-in. spacing bar provides a convenient and constant distance between the source and detecting crystal.

The second instrument is a multiple G-M tube instrument used to determine the radioiodine urinary excretion (Fig. 2). This instrument was designed because we wished an instrument that was less critical and because it was desirable to have a short time constant consistent with meter stability. The ten G-M tubes in this instrument provide a large-area array that makes placement of the radioactive material less critical.

The procedure for determination of thyroid-gland function is as follows: A solution of radioiodine containing approximately 1 $\mu c/cm^3$ is placed in a 500-cm^3 vacoliter bottle. When the patient reports for the tracer study, 20 cm^3 of the solution is pipetted into a paper cup for the patient's use. At the same time, a second 20 cm^3 is pipetted into the phantom plastic thyroid to serve as a standard. The patient is instructed to collect a 24-hr specimen of urine and return at that time. When the patient returns, the plastic phantom thyroid, which contains the 20-cm^3 standard, is placed at the end of the 14-in. spacing bar. The instrument is then set to read 100%. The phantom thyroid and its solution is removed and the patient is substituted for the phantom thyroid. The instrument then reads directly in per cent the uptake of radioiodine in the thyroid. The next step is to pour the 20 cm^3 of radioiodine from the phantom thyroid cup into a 2-quart wax milk container. This container is brought to volume with water and is placed directly in front of the multiple G-M tube instrument. This instru-

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ment is then set to read 100%. The patient's urine is poured from the mason jar into a similar wax container and is also brought to volume. This container is then substituted for the standard container and again the instrument reads directly in per cent the amount of radioiodine excreted in the urine.

The uptake percentage and the excretion percentages are added to determine the total amount of the administered dose that has been recovered. It has been our experience that we recover approximately 90% of the administered dose. When we have a percentage less than 90%, we feel certain there has been an error in collection of urine or the patients have a disease other than thyroid disorders that is holding iodine in the tissue spaces, such as cardiac decomposition or some form of nephritis.

Since this method is one of comparing an unknown source, either thyroid pickup or urinary excretion, with a known source, it becomes quite evident that scattered irradiation would be a big factor because of the relatively small number of scattered rays from the standard source in a paper cup as compared with the scattering from the structures surrounding the thyroid gland. Our first measurements were made with the standard dose held only in a paper cup. This gave total readings of 25–35% above the administered dose. We then used various types of phantoms in which the paper cup containing the standard could be immersed. Kaolin and sodium bicarbonate was first used; it was soon found that by using $1\frac{1}{4}$ in. of this mixture as a surrounding structure, we approximated the scatter from the average neck. This then led to trials of various thicknesses of plastic around the cup. We now have a phantom of plastic in which $1\frac{1}{4}$ in. of plastic surround the cup.

It also became evident that some filtration would be desirable to reduce the detection of the low-energy γ-rays and to increase the efficiency of the high γ-rays. This resulted in the use of one millimeter of lead filtration in front of the detecting crystal. This problem has been well covered by Dr. G. J. Hine *et al.* (*5*); this group recommended $\frac{1}{16}$-in. lead absorber and immersing the source in 2,000 cm^3 of liquid. We have duplicated their procedure and find that it certainly does improve the geometry; however, because the use of plastic is attended with less danger of spillage and also is much easier to manipulate, we have continued to use the $1\frac{1}{4}$-in. plastic surrounding the paper cup and find that it produces results well within diagnostic percentages.

In using the solution from the paper cup as a standard source for the urinary excretion in the 2-quart wax container, we find it wise to include the cup in the 2-quart volume because an appreciable amount of activity remains clinging to the sides of the paper cup that changes the reading of the standard, if one disposes of the cup.

This method has been checked with the usual scaler type of technique, and we find no discrepancies in the results. It is our opinion that our present method is even more reliable due to the fact that there is no chance for an error in calculation or a mistake in decay curves and other details familiar to all those who have done tracer studies.

In doing this work, we have had to be extremely careful in selecting those patients that have had a relatively iodine-free existence prior to the examination. With the physician selecting the patients carefully with regard to iodine ingestion, the conclusions drawn are that the use of radioiodine studies is especially important in the elimination or the proving of hyperthyroidism. We also feel that the tracer studies are of definite advantage over any other type in testing the thyroid function of children. It is our conclusion that a diagnosis of hypothyroidism is made with equal ease by the use of the basal metabolic rate as with the radioiodine tracers, with the exception of children. In this series of 1,800 tracer studies, 200 of them have had duplicate tracings after a 2-week interval. The results of these readings are within 5%, from which we conclude that the method is reproducible.

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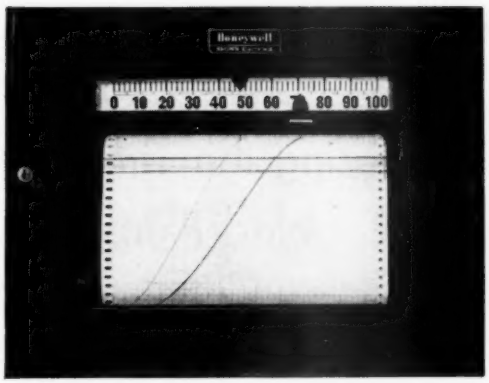

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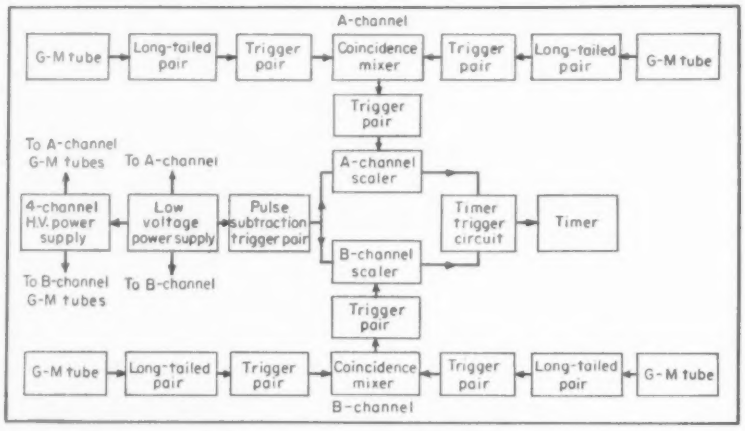

SCHEMATIC of viscometer timer

Measuring the Time of Fall of a Labeled Plummet

By A. J. ROGERS, J. W. HEYD, W. L. HOOD and J. A. WILLIAMSON
*Mound Laboratory, Miamisburg, Ohio**

Determination by radioactive means of the position of a plummet within a pressure vessel was used to measure the time of fall of a plummet in viscosity tests. With two pairs of coincident G-M counters, the position of a falling Co^{60}-labeled plummet was detected at two points in the vessel.

A shield assembly of machined steel blocks entirely encloses the G-M counters, except for narrow slits in the direction of the viscometer, to shield them from scattered radiation.

The upper pair of G-M counters initiates the timing cycle. Pulses are injected into the A channel of the coincidence timing circuit, where they are amplified, equalized, and applied to a coincidence mixer. The mixer generates an output pulse whenever pulses from the two counters occur within ~90 μsec of each other.

The lower pair of counters stop the timing cycle when the plummet is detected at the end of its fall path. Pulses from these tubes follow an identical path through the B channel.

Pulses out of the A and B mixers are applied to their respective trigger-pairs, which drive A and B scale-of-eight binary scalers. By means of an Eccles-Jordan trigger circuit, the A scaler output closes a relay and actuates a timer. The B scaler deenergizes the relay and stops the timer.

Premature actuation of the timer is prevented by injecting a resetting pulse (pulse obtained from a line-voltage-synchronized multivibrator) into all resetting grids of both scalers at a rate that prevents totalizing eight counts until the plummet is directly opposite the G-M tubes. Resetting pulse rates of 15, 20, 30, and 60 cps are provided to adapt the timer to various source sizes, background conditions, and G-M tube sensitivities.

The instrument has yielded test data reproducible to within ±1%. These data were obtained using a resetting pulse rate of 20 cps, a coincidence-circuit resolving time of ~90 μsec, and a Co^{60} source with a gamma flux equivalent to the flux from about 12 mg of radium.

* * *

This article is based on Mound Laboratory Report MLM-805 (1952). The authors wish to acknowledge the generous cooperation of Dr. J. R. Heiks during the development of the electronic equipment.

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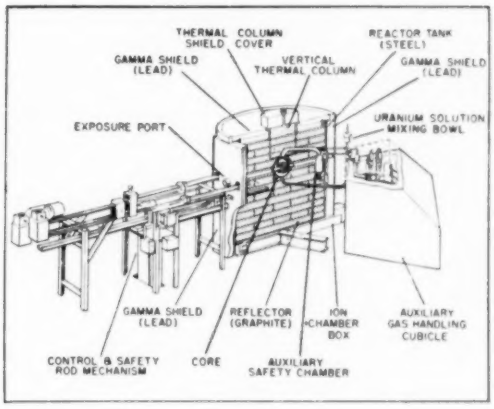

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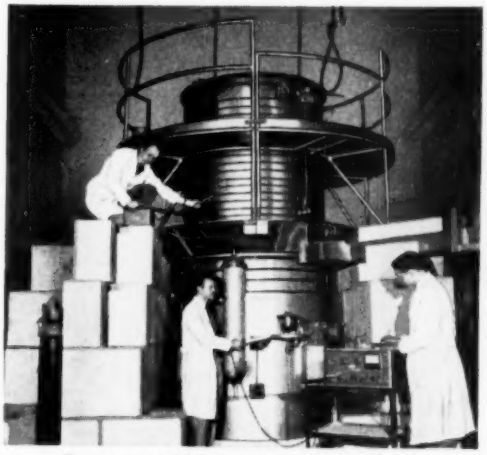

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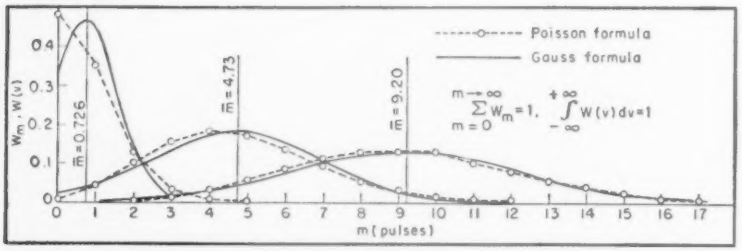

FIG. 1. Poisson and Gauss distributions calculated for three different expectation values. The Poisson distribution is defined only for whole numbers m, while the Gauss formula is represented by a smooth curve

Statistical Purity in Nuclear Counting

By OSWALD RIEDEL
Max-Planck-Institut für Chemie
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Many nuclear measurements involve counting of radioactive disintegrations with devices such as gas-multiplication or scintillation counters. As is well known, these disintegrations show statistical fluctuations governed by the Poisson distribution formula

$$W_m = \left(\frac{Nt}{m!}\right)^m e^{-Nt} \qquad (1)$$

where W_m is the probability that a certain number of pulses, m, is counted, N is the average or "expected" counting rate in pulses per second, and t is the counting period. On the average, $m_{avg} = Nt$ pulses will be counted in t seconds, but a single count yields a number m that generally differs from m_{avg}.

For not too small values of $m_{avg} = Nt$, the Gaussian distribution is a valid approximation to Eq. 1

$$W(v) = \frac{1}{\sqrt{2\pi Nt}} e^{-v^2/2Nt} \qquad (2)$$

where $W(v)$ is the probability that a certain v value will occur, where v is the "error" of a single count; $v = m - m_{avg}$.

Figure 1 shows that with increasing expectation value m_{avg} the Gaussian distribution approaches more and more the exact Poisson law.

Instrumental deficiencies in the counter (or its associated electronic circuitry) are sometimes obscured by these statistical fluctuations. It is however, generally possible by an analysis of a series of counts to ascertain whether the statistics are "pure," i.e., attributable only to the randomness of radioactive decay, or whether the statistics are "impure," reflecting defective counting apparatus.

For a "normal" distribution, such as given by Eq. 1 or 2, the standard deviation σ is given by (*2*)

$$\sigma = \sqrt{m_{avg}} = \sqrt{Nt} \qquad (3)$$

It is a measure of the breadth of the distribution. It means that 95.4% of all counts are within $m_{avg} + 2\sigma$ to $m_{avg} - 2\sigma$.

To examine the statistics of a series of counts several methods have been used.

The method of Bothe (*4*) is applicable to pulses that are recorded on a film or tape moving with constant speed. On such a record, the intervals between the single events are measurable, so that the grouping into 2, 3, 4 and more events may be compared with the mathematically calculated spacing in time. It should be mentioned that in this case as few as 1,000 single pulses are sufficient for a statistical purity test.

Most counting devices, however, give information only about the total number of pulses in a given time. Therefore, it is desirable to have available a quick and accurate technique for the analysis of measurements of this type for statistical purity.

It has also been proposed to compare the theoretically expected deviation with one calculated according to the method of least squares

$$\sigma_{exp} = \left(\sum \frac{v^2}{n-1}\right)^{1/2} \qquad (4)$$

For statistical purity, the "purity index" $p = \sigma/\sigma_{exp}$ would be expected to be equal to one.

But, as shown by Gauss (*3*), the rms deviation σ_{exp} itself has a mean error of $\pm 100/\sqrt{2n-1}\%$. Thus, to assay the statistical purity by the index method with an accuracy of, say, $\pm 1\%$, the large number of $n = 5{,}000$ counts and a correspondingly wearisome calculation of the error squares is necessary. Under such circumstances, a more economical method may be desired.

The Gauss formula for the error of σ_{exp} answers the question: How many counts must be made to find with a certain accuracy the parameter of the distribution curve of n counts, if it is sure —by knowledge or by faith—that the reigning error law is not only Gaussian but has also the proper parameter, i.e., $\sigma = \sqrt{m_{avg}}$. As shown by experience, spurious pulses of the kind not already obvious to a superficial observer, are mostly distributed at random. That is, the distribution remains Gaussian but is broadened. The broadening is

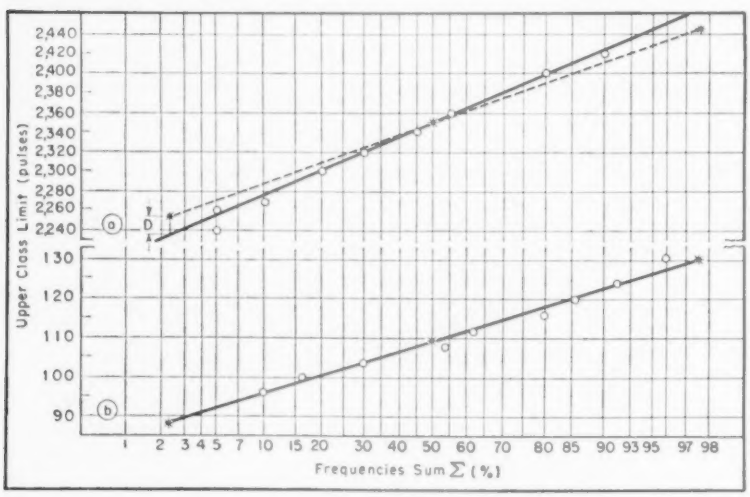

FIG. 2. Diagrams of the frequencies sum as a function of the upper class limit

not a random fluctuation, but a systematical deviation of the experimental points from the proper curve.

To perceive systematical deviations, however, only a few measurements are sufficient. While the purity index does not indicate that the deviations are systematical or random, the character of the deviations may be decided by comparing graphically the theoretical curve with the experimental points.

The distribution formula, Eq. 2, is hardly suitable for a graph, because it is a curved line; moreover, it is rather lengthy to calculate the distributions of Eqs. 1 or 2. Nevertheless, the method was used by Geiger and Rutherford (*1*). The whole process would shrink to a simple technique if it were possible to represent a Gaussian distribution by a straight line.

The method described here uses the Probability Integral Graph Paper* developed by A. Beckel (*5*). The advantage of this paper is that normal distributions that follow the integral Gauss curve $\int W(v)dv$ will appear as straight lines, and hence divergences can be readily observed. The values of the integral are given in per cent. The m-values, according to their size, are assigned to several classes of equal breadth; then, the filling of the classes is counted in per cent of the total number n of counts. The cumulative sum, called the frequencies sum Σ, that is reached at each upper class limit, is then plotted on the paper as a function of this upper class limit. If these experimental points conform to the theoretically expected distribution, they will lie on a straight line that will coincide with the line defined by m_{avg} and σ. These quantities can be determined by simple arithmetic.

The background pulses must not be subtracted from the counts, because the background is an independent statistically fluctuating source. This assumption may be tested, if necessary, by the same method.

Examples

The process can be clarified by means of line *b* of Fig. 2.

The (shortened) Table 1 contains the $n = 50$ counts. From these the arithmetic mean $m_{avg} = Nt$ is computed. The classes are scaled in such a way that the smallest as well as the largest m-values are included; in this example, these are $m = 93$ and $m = 130$. Table 2 contains the limits and contents of

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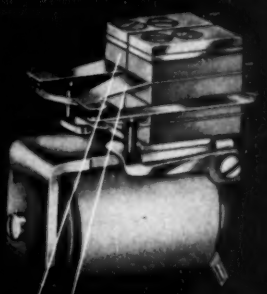

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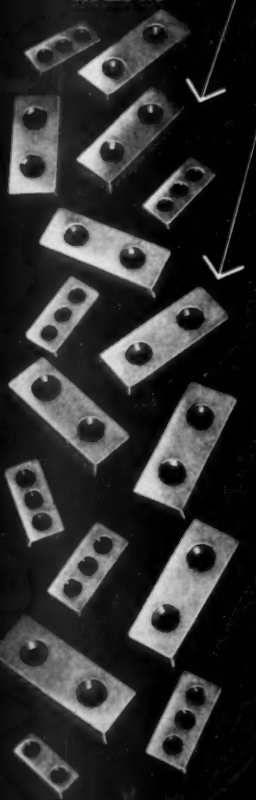

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the classes and the frequencies sum in per cent. In Fig. 2*b* the cumulative sums Σ are plotted from Table 2 as small circles. m_{avg} is plotted at $\Sigma = 50\%$; at $\Sigma = 2.3\%$ is plotted $m_{avg} - 2$ and at $m_{avg} + 2\sigma$ is plotted $\Sigma = 97.7\%$. Between $\Sigma = 2.3\%$ and $\Sigma = 97.7\%$ lie 95.4% of the population. These three points plotted as stars in Fig. 2*b* lie with the other ones on the same straight line; the apparatus in question, therefore, is functioning properly.

It is easily seen whether σ_{exp} deviates from $\sqrt{m_{avg}}$ by more than 5% in a plot of this type (with $n = 50$); even a comparatively small statistical impurity would be detected.

In Fig. 2*a*, which represents data from another apparatus, two straight lines are recognizable. In this example $m_{avg} = 2349.1$, $\sigma = 48.4$ and $n = 20$. The double standard deviation 2σ is too small by $D = 18$; σ_{exp} therefore is too large by 9. This difference cannot be due to errors in timing: countings were made for 20 periods of 240 sec each (the pulse rate was 9.788 per sec), and the timing is precise to about ± 0.1 sec. An error of this magnitude would explain an increase of the standard deviation σ_{exp} by at most 1.

The fact that m_{avg} itself has a mean error

$$\delta(m_{avg}) = \sqrt{m_{avg}/n} \qquad (5)$$

does not matter. In this example, indeed, $\sigma(m_{avg})$ is about 7, but the slope—and it is the slope that does not fit the experimental points—is known very accurately, since

$$\sigma = \sqrt{m_{avg} \pm \delta(m_{avg})},$$

according to the rule for the error of a function has, depending only on n, the error $\pm 1/2\sqrt{n}$. This has, for $n = 20$, the very small value of ± 0.11.

The apparatus that produced the counts plotted in Fig. 2*a* was not functioning properly. Since the experimental points lie on a straight line, the distribution is purely Gaussian, it is true, but the pulses are partly spurious. The G-M counter used had deteriorated and was close to the end of its life. This was shown by this test long before it became obvious.

The experimental standard deviation $48.4 + 9 \approx 57$ that was found graphically in this case would be theoretically correct for a much higher expectation value (about 3,300). Floating grids or fluctuating power supply voltages would cause similar effects.

The other case, in which the experimental standard deviation is too small, will occur when to the genuine pulses are added spurious counts that are not randomly distributed in time. Spurious pulses of this sort may consist of oscillations of amplifiers or pulse shapers that may be triggered by genuine pulses.

However, in the case of high counting rates, it is also possible to obtain a too small standard deviation attributable to the counter "deadtime." This question is discussed later.

It is recommended to make 50 countings and to divide them into 10 classes. Then, each class will have at least one entry so that double points are avoided. For example (a) of Fig. 2 only 20 countings were made and a class (the second in this case) has no entries, so that the content of the foregoing class occurs twice in the per cent table (in this case $\Sigma = 5\%$, the content of the first class).

TABLE 1—50 Countings 60 Sec Each

Count no.	m	*Class no.*
1	101	3
2	109	5
3	93	1
4	105	4
...	...	
...	...	
...	...	
49	130	10
50	104	3

$m_{avg} = 109.24$

$\sigma = \sqrt{m_{avg}} = 10.44$; $2\sigma = 20.9$

$\Sigma = 2.3\%$ at 88.3, 50.0% at 109.24, 97.7% at 130.1

TABLE 2—Class Contents

Class no.	*Limits under*	*upper*	*Content counts*	*%*	*Frequencies sum Σ (%)*
1	93	96	5	10	10
2	97	100	3	6	16
3	101	104	7	14	30
4	105	108	12	24	54
5	109	112	4	8	62
6	113	116	9	18	80
7	117	120	3	6	86
8	121	124	3	6	92
9	125	128	2	4	96
10	129	132	2	4	100
			50	100	

Very High or Low Rates

The procedures outlined previously are valid for pulse rates N that are low enough, so that the finite length of the individual pulses need not be taken into account.

The true number M of pulses is larger than the counted number m. If the length of a pulse is τ seconds ["defined deadtime" (*2*)], then

$$m = \frac{M}{1 + N\tau} \qquad (6)$$

and, the standard deviation σ becomes

$$\sigma = \pm \sqrt{\frac{m_{avg}}{1 + N\tau}} \qquad (7)$$

It is smaller than it would be without taking into account the pulse duration τ. In very high rate counting, τ must be known or has to be determined by one of the known methods (*6*).

On the other hand, as shown by Fig. 1, the expectation value m_{avg} should not be smaller than about 10, since otherwise the Gauss formula, basis of the graph paper, cannot be used. In other words: For very low pulse rates the periods t must be chosen long enough to contain a sufficient number of pulses.

Application

In analytical chemistry, one often must ascertain the occurring pulse rates N with a relative mean error of $\pm S\%$. A sample must be counted for a time t long enough that a number of pulses

$$Z = \left(\frac{100}{S}\right)^2 \qquad (8)$$

will be expected, $Z = Nt$. The necessary counting times t are given by formulae, *cf* (*7*), or by nomograms, *cf* (*7*) and (*8*). By the graphical purity test, the $\sigma(Z)$ are known with a percentage error $\pm\mathcal{E}$, and so are also the values of S

$$S \rightarrow S\left(1 \pm \frac{\mathcal{E}}{100}\right) \qquad (9)$$

As noted previously, $\mathcal{E}$ is $\leqq \pm 5\%$ (for $n = 50$).

The purity test will usually be made during a series of actual sample counting. The counts of a constant standard sample that are scattered over the whole series are then subjected to the test. The meaning of Eq. 9 is that the error $\mathcal{E}$ plays no role for choosing the numbers Z properly according to Eq. 8.

The extent to which a statistical impurity may be allowed in actual counting determinations depends on the trustworthiness that will be claimed for the values of the sample strengths measured with the apparatus in question. In any case, a difference between σ_{exp} and $\sqrt{m_{avg}}$ is a sign for an improper function that will, in general, falsify to some extent the numbers Z of counted pulses. In Fig. 2*a*, σ_{exp} is larger than $\sqrt{m_{avg}}$ by 19%, and measurements that are made with this apparatus should be rejected. For a small difference of, say, 6%, the results are less doubtful; they may be accepted unless a high accuracy of the sample rates N is demanded, e.g., if an error $S = \pm 5\%$ is permitted.

There might be, for the same apparatus, a statistical impurity for high pulse rates N but not for low rates. The standard sample for the purity test should have, therefore, a pulse rate that approaches the highest rate that occurs in the actual sample countings but that is not yet so high that the pulse duration τ must be taken into account.

* * *

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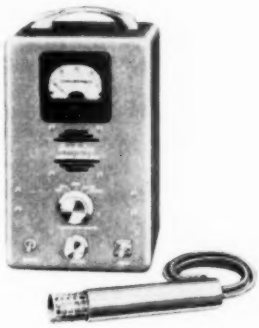

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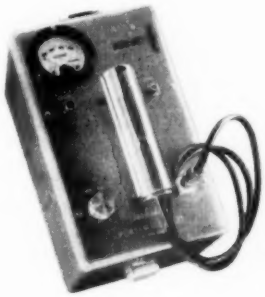

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Compressive Properties of Uranium

By NICHOLAS GROSSMAN and SEYMOUR PRICEMAN
Atomic Energy Division
Sylvania Electric Products, Inc.
Bayside, New York

Many of the analytical expressions used in fuel-element design assume that uranium's modulus of elasticity in compression is identical in value to the modulus in tension. The tests described here verify the validity of this assumption and determine the compressive values of uranium's Poisson's ratio, shear and bulk moduli, modulus of resilience, proportional limit, and yield strength. Effect of strain hardening also is investigated.

The Tests

Specimen A (Rockwell C 15) came from one ingot; specimen B (C 18) from another (see Fig. 1). Both were machined from hot-rolled wrought uranium bars. Tests used the 24,000-lb full-scale dial setting (smallest division = 20 lbs) on a 60,000-lb-load-capacity machine. Strains could be read to 10 μin./in. and estimated to the nearest 5.

Top and bottom surfaces of the specimen were lubricated with molybdenum disulfide. A hemispherical head was fitted in the upper head of the testing machine, and the specimen was placed between two hardened-steel flat plates. During the test, absence of any bend-inducing load eccentricity was verified by reading individually the four strain gages that were used. Three loading-unloading cycles were run on each specimen.

Stresses were computed using the nominal cross-sectional area. Since maximum stress was about 35,000 lb/in.^{2}, these stress values differed from average true stress by less than 1%.

Stress-strain curves for low-stress regions of the initial loading are shown in Fig. 2. Complete stress-strain curves are shown in Figs. 3 and 4. Longitudinal and transverse stress-strain curves and the ratio of transverse to longitudinal strain (Poisson's ratio) are plotted in Figs. 5 and 6.

Results

The curves indicate that: 1, the curve for hot-rolled uranium in compression is linear up to about 3,000 lb/in.^{2} stress; 2, the compressive modulus of elasticity is 25.5×10^6 lb/in.^{2} (this value is about the average for those reported in tension) (*1*); 3, Poisson's ratio is not a constant, but a function of the applied stress (the average value for the two specimens extrapolated to no stress is 0.20 and increases as the stress is increased) (*2, 3*); 4, there is no artificially-induced elastic portion of the stress-strain curve after the initial loading.

Taking the average values for $E = 25.5 \times 10^6$ lb/in.^{2} and $\mu = 0.20$, the shear modulus $G = E/2(1 + \mu) = 10.6 \times 10^6$ lb/in.^{2}, and the bulk modulus $K = E/3(1 - 2\mu) = 14.2 \times 10^6$ lb/in.^{2} The modulus of resilience $U_r = S_p^2/2E$

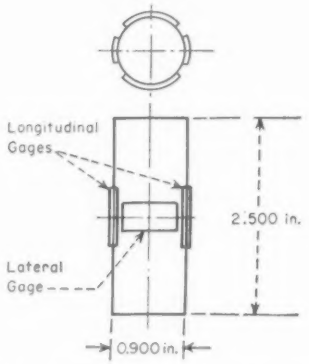

FIG. 1. Specimen size and strain gage location

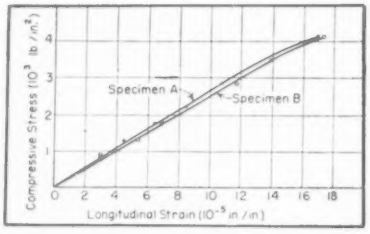

FIG. 2. Stress-strain curves in low-stress region for both specimens

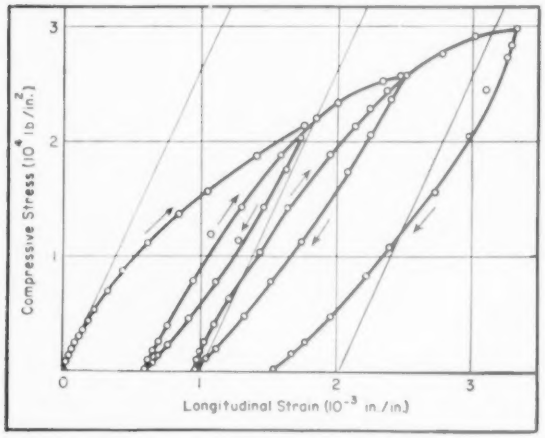

FIG. 3. Complete stress-strain curve for specimen A

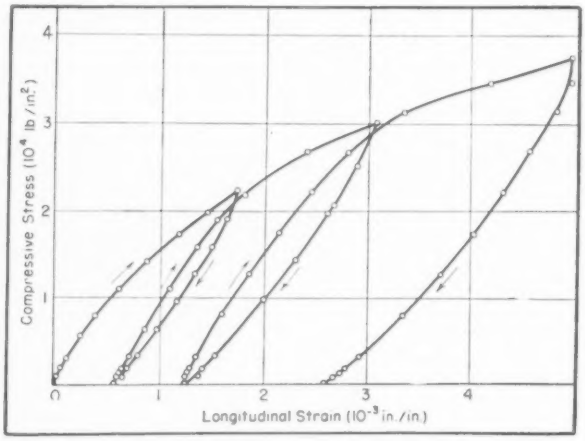

FIG. 4. Complete stress-strain curve for specimen B

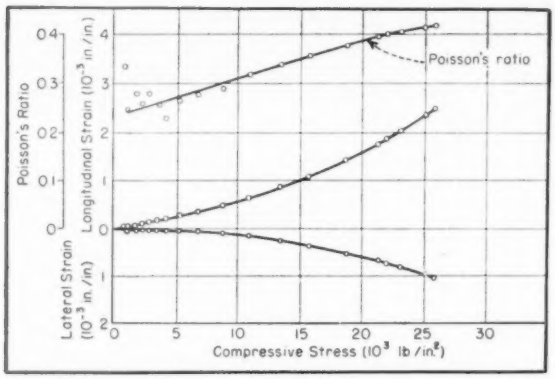

FIG. 5. Longitudinal and transverse stress-strain curves and Poisson's ratio for specimen A

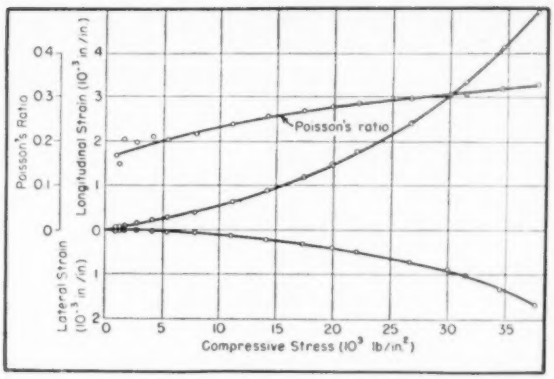

FIG. 6. Longitudinal and transverse stress-strain curves and Poisson's ratio for specimen B

= 0.176 in.-lb/in.^{3}, which compares with 15.0 in.-lb/in.^{3} for mild steel, or a ratio of almost 1 to 120.

Discussion

There is a very low, but well defined, proportional limit (3,000 lb/in.^{2}). No experiments were conducted to test for the existence of an elastic limit. For all engineering purposes, the moduli of elasticity in tension and compression are identical, and analytical expressions using this as a basis can be utilized. Poisson's ratio is not a constant, but steadily increases with increasing stress. This is typical for semiplastic metals, which in the limit for the perfectly-plastic stage approach the value of 0.500. The relatively low value of 0.20 lies close to recently-reported values for mild steel (0.23 to 0.25) (*4*).

The values for the bulk modulus of compressibility obtained in this investigation are in much closer agreement with those obtained by Bridgman by his well known extreme-high-pressure testing techniques (14.56×10^6 lb/in.^{2}) (*5*) than are the values from ultrasonic tests (*1*).

Data from this investigation are useful in evaluating the accepted graphical method of determining yield strength. Yield strength is defined as the stress at which a material will be permanently strained a specified amount, usually 0.1 or 0.2%. This value was devised primarily for materials that do not have a definite yield point, which is the case with uranium. This method assumes that a straight line between the endpoints of an unloading curve from a particular stress to zero stress will conform closely in slope to the initial stress-strain curve.

Although this assumption may be valid for other materials, Figs. 3 and 4 show that use of the graphical method for uranium gives results lower than the actual values. The actual values of yield strength (lb/in.^{2}) as approximated from Figs. 3 and 4 are 27,000 for 0.1% offset and about 33,000 for 0.2% offset; the graphical method gives values of 22,600 and 29,900.

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3. E. R. W. Jones, W. Munro, *J. Mech. Phys. Solids*, **1**, No. 3, 182 (1953)
4. W. D. Manley, *Iron Age* **171**, No. 17, 148 (1953)
5. P. W. Bridgman, "The Physics of High Pressures," p. 161 (Macmillan Co., New York, 1931)

REACTOR FACTS

• **Boiling water reactors,** according to recent studies, will probably operate better with heavy water than with light water as coolant-moderator. The fuel plates are farther apart in the D_2O design; this permits more favorable boiling performance.

• **Breeding of U^{233}** from thorium is most readily accomplished by thermal reactors; fast reactors are best for breeding plutonium from U^{238}.

• **Byproduct plutonium** or U^{233} purchase at rate of $25–30 million per year for 15 years is being considered by AEC to encourage industrial participation in power reactor development.

• **Package reactor's** fuel loading is expected to cost $1-million, the plant $2.5–3-million.

• **Swiss research reactor** will be built jointly by industry and government. The 10-Mw heavy-water reactor will be used for industrial studies of heat transfer, materials, and instrumentation and for training and radioisotope production. Natural uranium and about 9.5 of the needed 12 tons of D_2O will be imported.

• **Experimental fuel fabrication** facility to be built at Argonne will be used for breeder-material recycling studies. Tests with the $1.5-million plant will involve simple methods of partial processing and refabrication without complete removal of radioactivity. AEC Commissioner E. M. Zuckert has stated that these methods "could mean nuclear fuel at costs in the order of 1 mill/kwh even in those reactor designs which require somewhat enriched, thus more expensive fuel."

• **Canada's NRX** reactor, back in operation after a 14-month shutdown, is now producing 40-Mw. This is a 33% increase. In addition to the NRU reactor, now under construction, Canada plans to operate a pilot nuclear power plant within 3 years. Based on experience with this unit, a plant will be built by 1962 to supply the southern Ontario power grid with 6-mill nuclear power. By that time, present and planned hydroelectric plants will be outstripped by the area's 6% per year increase in power demands.

• **Two French production reactors** are expected to supply 75 lb of plutonium per year. The 100-Mw units will be built in the Rhone valley.

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Patents

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Printed copies of the letters patent may be obtained from the Commissioner of Patents, Washington 25, D. C., at 25 cents a copy, payable by check or money order. Specify the patent number and title when ordering.

These abstracts have been furnished by the Index of Inventions, maintained by the Government Patents Board, Washington, D. C.

Transmission fluorimeter* (2,663,801), M. Slavin, M. H. Fletcher, M. Irving—Apparatus for analyzing solid and gaseous materials measures fluorescent light due to ultraviolet excitation of a thin sample. Minimized ultraviolet source-to-detector distance permits compact fluorimeter utilizing small source.

Neutron detector* (2,663,802), P. E. Ohmart—Radiation detector includes electret between pair of electrodes with its opposite faces conductively coupled to electrodes. Arrangement provides for detecting and counting voltage transients induced in electrodes by changes in volume charge of the electret responsive to neutron bombardment.

Container for neutron irradiated material* (2,664,998), J. F. Gifford, N. B. Garden—Container comprises outer cylindrical aluminum casing enclosing inner platinum container and having enlarged upper extension offset by a shoulder. Extension has upwardly flaring funnel closed by a thin cap. Funnel holds liquid during opening to cover irradiated material when cap is punctured.

Ion accelerating and focusing system* (2,665,384), H. P. Yockey—Apparatus for accelerating and focusing ions, e.g., separation of isotopes, comprises three electrodes, each having openings aligned to produce focusing of ions. Inner electrode has narrow slot and is maintained at high potential. Intermediate electrode, with opening smaller than slot, is held at high negative potential for accelerating ions. Outer electrode has larger opening than slot and is maintained at potential intermediate to that of other electrodes to decelerate ions.

Dynamic displacement meter† (2,665,581), C. H. Kean—Meter for indicating dynamic displacement of vibrating body, e.g., piezoelectric crystal, comprises apparatus for applying displacement and voltage driving crystal on axes of oscillograph, giving plot of displacement vs applied voltage.

Vacuum tube amplifier for measuring signals having a large variation in level† (2,666,098), J. L. Leonard—Device utilizes amplifier having attenuator in input and pair of electronic relay circuits responsive to signals of different levels; it includes adjusting means to decrease or increase level of signal input in response to one or the other relay circuits.

Spectrometer* (2,666,147), L. B. Borst—Neutron spectrometer utilizes cylindrical crystal reflector having concave reflecting surface toward source of radiant energy. Focal point of beam can be adjusted by changing reflector radius of curvature. Neutron-beam intensity indicator is provided.

Rapid operation air lock for closed vessels* (2,666,539), R. T. Avery—Air lock, e.g., for vacuum vessel of mass spectrometer, comprises chamber sealed over aperture in wall of vacuum chamber and having spring-loaded closure on sliding rod movable into sealing contact over aperture.

Container having a distortable flow control means† (2,666,545), J. J. Hopfield—Glass gas container has long neck housing tube having helicoidal crack. One end of tube is closed and secured to neck; other end is open and attached concentrically to surrounding portion of tube. Crack is normally closed but may be opened by forcibly twisting tube so that it serves as flow-control valve.

Survey instrument* (2,666,865), C. J. Borkowski—Radiation detector comprises hollow casing having handle at one end, window in one side and central conductor. Open frame slides over

window and carries porous shield to prevent dust from entering casing. Metal mesh mounted on frame coextensive with shield maintains uniform electric field about conductor. Associated are amplifier, pulse circuit and earphones.

Electronic frequency vernier† (2,666,899), L. D. Smullin—Device includes stable reference oscillator, calibrated variable frequency oscillator and modulator. Variable oscillator and modulator produce amplitude modulation of reference oscillator output. System indicates coincidence between known sideband frequency and unknown frequency.

Mass separator* (2,667,582), J. G. Backus—Four curved electrodes, symmetrically positioned parallel to ion-beam path from ion-current source, establish uniform electrical field by which ions are focused on receiver.

Energy proportional counting of exterior radiation‡ (2,667,586), H. Kallmann—Device for measuring energy absorbed by object in radioactive field comprises scintillating crystal, phototube, and counter circuit. Distance between crystal and tube may be adjusted so that only one count is registered each time energy quantum of maximum value excites crystal

Ion source* (2,668,260), Clarence F. Barnett, Carroll B. Mills—Source for use with particle accelerator comprises carbon-anode envelope and pair of thermionic cathodes at opposite ends of envelope. Magnetic field around cathodes produces low-voltage, high-density arc. When bombarded with positive ions, cathodes emit electrons.

Voltage regulator* (2,668,272) Edward J. Groth, Jr.—Circuit includes means to produce output voltage of desired value, detector, and two-channel amplifier. Amplifier output controls variable resistance in series with voltage source.

Sylphon sealed pump* (2,668,656) Eugene T. Booth, Jr., Hugh C. Paxton—Reciprocating pump for handling corrosive gases. Piston is provided with peripheral flanges to reduce leakage, the cylinder having recesses at the ends to receive the flange.

* Administered by Chief, Patents Branch, Atomic Energy Commission, Washington 25, D. C.

† Administered by Patent Counsel, Department of the Navy, Washington 25, D. C.

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BOOKS

Annual Review of Nuclear Science, Vol. 3

Edited by JAMES G. BECKERLEY (Annual Reviews, Inc., Stanford, 1953, x + 412 pages, $7.00). Reviewed by W. F. LIBBY, University of Chicago, Chicago, Illinois.

This third volume of a most valuable series of review books maintains the high standards set by the first two volumes published in 1951 and 1952. The opening chapter, written by Henley, Ruderman and Steinberger on *Reactions of π-Mesons with Nucleons* is a rather detailed and very up-to-the-minute account of the subject. The reviewer had the feeling that experts in the field would be satisfied with this article, and he found himself satisfied for reasons of the coverage and clarity of presentation.

The second chapter, by Leprince-Ringuet, on *Mesons and Heavy Unstable Particles in Cosmic Rays*, is an excellent discussion of a most fascinating subject. The existence of new particles is deduced by a single track in a particularly fortunate photographic plate. There is very little more dramatic in science than the life of the cosmic ray physicist establishing new particles and studying their characteristics.

The remaining chapters include *Extranuclear Interactions of Electrons and Gamma Rays* by Corson and Hanson, *Neutron Optics* by Hughes, *The Standardization of Neutron Measurements* by Wattenberg, and a series of chapters on photographic emulsions, radiation chemistry, hot-atom chemistry, separation techniques in radiochemistry, and finally five chapters by biologists and radiobiologists on the effects of radiation and also on the measurement of radiation doses.

The functions of review volumes such as this include introduction of new graduate students to subjects as well as the assistance of the seasoned research worker in maintaining his acquaintanceship with the literature. Most of the articles in this volume would serve the first purpose as well as the second. One or two are a little bit too advanced in character for the beginning graduate student. There are no doubts in the reviewer's mind that this book is well worth the purchase price for anyone engaged in research in nuclear physics. It is probably true that most of the people working for the Atomic Energy Commission have enough interest in the subject to benefit from at least a brief perusal of the volume.

The whole volume, like its two predecessors, is slanted towards the nuclear physicists and the practitioner in this field. The articles on hot-atom chemistry by Willard and on radiation chemistry by Magee are excellent accounts which chemists would find extremely interesting reading. The rest of the material is definitely of interest principally to nuclear physicists and nuclear engineers.

It is interesting in comparing the first two volumes with the third to note the progress in certain fields. The maintenance of the style originally set makes this comparison simple. Continuity is good despite the variations in authorship.

This series, like the other publications of the Annual Reviews, performs an important function as a literature source. The references given at the ends of the articles are particularly useful to graduate students and research men in general in reading the modern literature in any given subject. It seems clear that all libraries professing to cover technical literature to any degree at all should possess this book and its predecessors and successors.

Planning Guide for Radiologic Installations

THE AMERICAN COLLEGE OF RADIOLOGY (The Year Book Publishers, Inc., Chicago, 1953, xvi + 336 pages, $8.00). Reviewed by HANSON BLATZ, Health and Safety Laboratory, New York Operations Office, U. S. Atomic Energy Commission.

This unique volume is in the form of a symposium by some 50 leading experts in all of the phases of medical radiology and its related fields, including radiological physics, architecture, equipment manufacture and hospital administration. It appears that few, if any, of the problems arising in the establishment and operation of an office or institutional department devoted to radiology are left unanswered. Most of the authors have had extensive experience, which is evident in the painstaking detail with which the chapters were prepared. A complete evaluation of this volume would require the critic to be a physician, physicist, architect and accountant all rolled up in one.

The guide consists of 22 independent essays on as many different subjects, covering a wide range of items extending from the nuclear properties of radioactive bromine to a discussion of the circumstances under which a radiologist may claim a cocktail party as a legitimate professional expense. In the technical sections, of most interest to NUCLEONICS readers, there is a wealth of material on radiation properties and shielding.

Although the chapter on *Radiation Protection* covers the subject as it relates to X-ray, radium and radioactive materials quite completely, the same subject is dealt with in seven other chapters by other authors with some diversity of opinion. For example, there seems to be some disagreement as to whether there should be an unqualified condemnation of mobile leaded floor screens for X-ray shielding and whether or not all dental X-ray controls should be located in separate booths.

It was particularly gratifying to see in print for the first time the use of occupancy factors in shielding requirements. The common assumption that all possible accessible places should be considered as occupied for 48 hours a week, indefinitely, with the radiation source in its most unfavorable position has frequently resulted in fantastic shielding costs in the past which have often been unnecessary. The extensive tables on secondary protective barriers should prove particularly useful in providing a more practical approach to the X-ray shielding problem. In another chapter, the statement is made that no X-ray units are manufactured that meet NFPA requirements for operating-room use. This is in disagreement with one leading equipment manufacturer's claims, although it probably was correct at the time of preparing the text.

It would have been helpful to see a more thorough treatment of the ventilation of an isotopes laboratory, a subject that is omitted from the excellent chapter on *Ventilation and Air Conditioning* and mentioned but briefly in the chapter on *Radioisotopes Laboratories*. Similarly, some discussion of radiation instrumentation would appear to be appropriate, especially since a pattern is set by a detailed discussion of darkroom accessories.

One might take issue with the need for over a hundred pages of reproduced Bureau of Standards handbooks

in the appendices, including their many plates, some of which are identical with plates in the text and with each other, when the original handbooks may be purchased from the Government Printing Office for a very nominal sum. The reproduction of Handbook 41 does not include the important May, 1950, corrections. That of Handbook 54 is from a preliminary draft, and the final report (of which this reviewer is a co-author) contains significant changes.

Considering everything, this volume is undoubtedly the most complete and well balanced omnibus type of book (a type becoming more and more popular in technical fields) to be offered recently. It is a must for any worker in the field of radiology who wishes to keep abreast of modern planning.

Dislocations in Crystals

By W. T. READ, Jr., (McGraw-Hill Book Co., Inc., New York, 1953, xvii +228 pages, $5.00). Reviewed by JOHN C. FISHER, Engineering Services Div., General Electric Co., Schenectady, N. Y.

Twenty-five years ago, crystal imperfections called dislocations were introduced into physics to help explain the mechanical weakness of crystals. At first, dislocation theory was relatively simple and qualitative, and accounted in a general way for the softness and plasticity of metal crystals. As time went on, the theory became more complex and quantitative. It was discovered that not only could yielding and strain-hardening of crystals be understood in terms of dislocations, but that crystal growth and grain-boundary energies and motions also could be understood.

Dislocation theory is in a period of rapid growth. Some applications of the theory are well worked out, experimentally verified, and generally accepted, whereas others still are quite speculative and controversial. In his book Read has gathered together those aspects of dislocation theory and application that have passed beyond the speculative stage, and that will remain valid in the future.

The book is divided into two parts. In the first, dislocations and dislocation theory are described and developed from the first principles. The crystallography, topology, energies and kinematics of dislocations and their motions are discussed. In the second, the well-founded applications of the theory are presented. Crystal growth, grain-boundary energies and grain-

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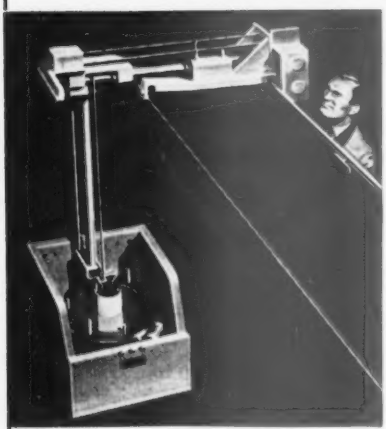

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boundary motions are treated in detail. The processes of plastic deformation and work hardening, on the other hand, for which dislocations were introduced in the first place, are not discussed as applications of the theory, although the main ideas relating to these processes are presented at a number of places in the book.

I believe Read's book to be an excellent development of dislocation theory, equally suitable for those unfamiliar or familiar with the field. The applications of the theory are clear cut and highly instructive. The reader is prepared, after reading the book, to follow the further development of the theory, and in particular to exercise his judgment with respect to those applications of the theory, such as plastic deformation, that still are in a speculative and controversial stage.

BOOKS RECEIVED

Physics and Applications of Secondary Electron Emission, by H. Bruining, McGraw-Hill Book Co., Inc., New York (Pergamon Press Ltd., London), 1954, xii + 178 pages, $5.00. This book surveys the physics and applications of secondary electron emission. The first seven chapters are devoted to the physical side. The last three chapters deal with the application of electron multiplication, elimination of disturbing effects due to secondary electrons, and electrical-charge storage devices utilizing secondary electron emission.

Active Networks, by Vincent C. Rideout, Prentice-Hall, Inc., New York, 1954, xvi + 485 pages, $10.65. In covering the fundamentals of the subject, the author utilizes four-terminal network analysis. Although emphasis is on vacuum-tube circuits as applied to communication and control engineering, the transistor is treated in considerable detail. Sections are included on thyratrons, magnetic amplifiers, and position-control servomechanisms.

ALSO OF NOTE

Translations available. A list of translations in the Special Libraries Association Translations Pool is available. The 73-page list comprises 1,100 translations in the Pool as of Oct. '53. An addendum to cover several hundred translations contributed in the interim will be issued shortly. *S. L. A. Trans-*

Correction

During preparation of the cover of the April, 1954, issue of NUCLEONICS, a decimal point and the numeral 1 were omitted. The bottom of the performance index scale should be labeled 0.1, not zero.

lations Pool, John Crerar Library, 86 E. Randolph St., Chicago 1, Ill. (include $0.30 to cover postage).

Protection Against Betatron-Synchrotron Radiations Up to 100 Million Electron Volts (NBS Handbook 55). This handbook presents recommendations by the National Committee on Radiation Protection. Protection requirements for operating personnel, hospital patients, and the public against the potential hazards of the accelerators are outlined. Recommendations are also given for a consistent system of units and of measurement procedures that can be applied to radiations with energies above 5 Mev. *Government Printing Office, Washington 25, D. C., $0.25.*

Lead Handbook for the Chemical Process Industries. Chemical and physical properties of lead and lead products are given in tables that include: physical, thermal, and electrical properties of lead; safe working pressures for piping; sulfuric acid data; eutectics of lead; and lead thickness vs X-ray protection. Other information for various materials is: conversion tables for mechanical, electrical, heat, and chemical units; heat transfer data; properties of useful metals; and weights of various materials. Recommended construction methods and typical installations are given for lead-lined construction. *Federated Metals Div., American Smelting and Refining Co., 120 Broadway, New York 5, N. Y.*

Government publications: **Measurements of Radioactivity** (catalog No. C13.4:476, $0.45), **Safe Handling of Radioactive Isotopes** (catalog No. C13.11:42, $0.20), **Control and Removal of Radioactive Contamination in Laboratories** (catalog No. C13.11:48, $0.15), **Atomic Power and Private Enterprise** (catalog No. Y4.At7/2:En8, $1.25), **Radiological Monitoring Methods and Instruments** (catalog No. C13.11:51, $0.15). *Superintendent of Documents, Government Printing Office, Washington 25, D. C.*

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AEC's Top Management:

Strauss-Nichols Team Molds Atomic Program

AEC's Strauss (left) and Nichols

Atomic Energy Commission—like the bombs it produces—packs a powerful wallop for its size.

With a staff numbering less than 6,500, AEC manufactures bombs and warheads that form the basis of the whole "new look" military strategy. By the middle of next year, this tiny organization will be directing operation of some $7-billion worth of plants and guarding stockpiles of several billion dollars worth of fissionable material. Construction program of AEC this summer will account for around 5% of all construction spending in the country. By next winter it will be using nearly 10% of all the electric power produced in the nation.

On top of all this, legislation now before Congress would hand AEC vast regulatory and control powers over a brand-new nuclear power industry.

Masterminding this huge atomic energy empire, which extends all the way to the uranium mines of the Belgian Congo, are two $20,000-a-year subcabinet government employees.

Directing the broad policy of the agency is AEC Chairman Lewis L. Strauss, investment banker, World War II admiral and long-time public servant. As head of the 5-man Commission, he is roughly equivalent to the chairman of the board of this $12-billion public enterprise.

Translating Commission policy into bombs, warheads, powerplants and X-ray machines is K. D. Nichols, a retired Army Corps of Engineers general and a moving force of the wartime atomic bomb project.

The Strauss-Nichols team directs and controls the nation's atomic energy operations. Strauss, an often-dissenting member of the original AEC, came back as chairman last July 2. Nichols, who had been a consultant and boss of special weapons projects since he stepped out of the atomic bomb project in 1947, was brought in as AEC general manager last November 1.

The team is already putting its own brand mark on AEC policy and operation.

As a minority member of the original AEC, Strauss was one of the two commissioners who fought for development of the hydrogen bomb. He talked AEC into setting up a detection system to measure atomic blasts of other nations. In the background was his continual plea for tighter security measures. He still credits Russian espionage with a big role in their nuclear weapon development.

The new chairman, who runs a nearby Virginia farm on the side, is known more for his backbone and persistence than for his aggressiveness. Even as a dissenter in earlier Commission service, Strauss stayed on until his views were adopted by former President Truman over AEC's majority.

The new general manager is less of a public figure, although no one would accuse him of reticence. Before a Congressional appropriations committee, it is Nichols who does the catching for the AEC delegation. His answers at sessions this year display a broad grasp of nearly all AEC operations.

His strong, sometimes aggressive, character has lead law-makers to tag him as "the first AEC general manager who really acts like a general manager." His new subordinates at AEC admit that he is a man who can and does make decisions with a minimum of fuss.

The Strauss-Nichols team is no accident of government patronage. They come about as near being career men in the U. S. atomic program as it is possible for top AEC officials to be.

Strauss, one of the few rear admirals in the Naval Reserve, was the naval expert on atomic energy during the wartime A-bomb project. As a member of the original AEC, he served from 1947 until 1950. He was brought back to Washington early last year as President Eisenhower's special advisor on atomic energy and moved into the chairmanship in early July.

Nichols, a scholarly engineer, was the second officer assigned to the Manhattan Project, which developed and produced the first A-bomb. He later was in charge of research, development, design and construction of the unprecedented gaseous diffusion plant at Oak Ridge and the production reactors at Hanford, which turned out material for the first A-bombs. He was with the Manhattan Project until it was turned over to the newly-created AEC in January of 1947.

Nichols served successive stints as consultant on atomic energy matters to the U. S. delegation to the United Nations, to the Joint Congressional Committee and to the Military Liaison Committee. He was also boss of Army special weapons projects including the atomic cannon and guided missiles. Strauss brought him into AEC last fall.

Strauss or Nichols—or both—have played a key role in:

- Helping to promote the plan for an international agency to push peacetime uses of atomic energy.
- Proposing legislative changes to foster industrial nuclear power development and permitting exchange of limited atomic information with friendly nations.
- Tightening-up AEC organization and its operations.
- Spurring industry interest in atomic power development.
- Tightening public information procedures and coordinating government statements on atomic energy matters.

Industrial power. President Eisenhower, when he named Strauss to head AEC, is reported to have urged him to get the civilian nuclear power program into high gear. White House legislative proposals to foster industrial development of atomic power substantiate that report.

Strauss undoubtedly has added impetus to a program that started several years ago. He is known as a prime

mover in getting H-bomb development underway. With his cultivated sense of history, there is reason to believe that he wants his term as chairman to be remembered for its development of the peacetime uses of atomic energy.

As far back as 1946, when the present atomic energy act was being written, he expressed the hope that this new energy source would be eventually harnessed for use by free American enterprise. Strauss saw the federal monopoly over the source as a temporary expedient for building military defenses.

This view, fairly widely known in industry, may help to account for a share of the new spurt of enthusiasm industry is displaying for nuclear power.

An informal survey conducted early last year by AEC Commissioner Thomas E. Murray convinced the Commission that private industry was not prepared to make immediate sizable financial contributions to nuclear power development. About the same time, Congress gave the government program a big push by allocating some $7-million for development and construction of a large-scale civilian nuclear power plant.

In early December of last year, with Strauss in as Chairman, AEC issued a formal invitation for industry to invest in the $45-million Pressurized Water Reactor, which was being designed by Westinghouse Electric Corp.

The response caught even the enthusiastic staffers and Commission members off guard. Nine firm, broad-scale offers were made for investing and participating in construction and operation of the PWR. In announcing acceptance of the Duquesne Light Co. bid, which AEC picked as the most favorable, Strauss estimated it would save $30-million in government funds.

During this same period, AEC was grinding out a five-year power reactor development program. This program, approved by Congress in March of this year, marks the first time that a formal program of this type had been put down in black and white by AEC.

The legislative proposals, drawn up by AEC and presented to Congress by the President, were still another basic step in getting the industrial nuclear power program rolling. If all or even a part of these proposals are written into law this year, part of the credit must go to AEC and the Strauss-Nichols team.

In a similar manner, Strauss and

Washington Report

With public hearings under way on proposals by the Joint Committee on Atomic Energy to amend the Atomic Energy Act, the following broad conclusions can be drawn:

▶If the first version of the bill were passed as written, a vigorous atomic energy industry could be started.

▶The bill contains some provisions unacceptable in their present form to at least one point of view—either the Joint Committee, AEC or industry.

In most cases, these provisions were written into the bill because agreement couldn't be reached in committee and a point of view was needed to facilitate public discussion. In other cases, the Joint Committee wanted to get a principle across.

▶Barring filibuster tactics, a compromise bill satisfactory to the principal parties will be reported out by the Committee at the conclusion of the hearings. The committee staff has been working nights incorporating certain recommended changes with a view to coming up with a first revision of the bill that may be published even before the end of the hearings.

▶Although the AEC-proposed bill has not been made public and AEC views on the Committee bill have not been heard in public, AEC's position on Committee proposals can be deduced from a rereading of the President's message of Feb. 17 (NU, Mar. '54, p. 74).

An analysis of the various views points towards a shakedown on the controversial provisions as follows:

▶Private firms will be permitted to receive licenses to build, own and operate power reactors. The only opposition to this comes from the small minority opposing any industrial participation at all.

▶The government will lease fissionable fuel to industry. Although there are some in industry who feel actual ownership of fuel is vital for financing and simplification of administration, most will accept leasing assuming appropriate guarantees on the availability of fuel. If for no other reason than the political infeasibility of fuel ownership at this stage of development, the Joint Committee will not yield on this one.

▶Licensing powers of AEC and AEC controls on fuel will be made more definitive. Industry objects strongly to broad, nonspecific powers given to AEC. The Committee sustains industry on this.

▶A compromise will be reached on patents. Normal patenting, proposed in the bill, is supported by industry but is questioned by at least three or four members of the Committee. Chairman Cole rules out compulsory licensing as being un-constitutional and has spoken out for normal patents. There will probably be some stipulation whereby no company will be permitted to gain a patent that would be unusually restrictive on the growth of the industry—at least during the early years.

▶The proposed review board to hear complaints about AEC actions will not get into the final bill in its present form. AEC vehemently objects to having a board "look over its shoulders" and be the one to make ultimate decisions on licensing actions. AEC prefers that appeals go to the courts, but this overlooks the problem of trials necessarily involving restricted data. Some halfway measure will have to be found.

▶Proposed "three-year life" for restricted data will be knocked out completely. Instead, strong statements authorizing and encouraging AEC to declassify and disseminate information will be inserted.

▶Requirement that AEC report to Congress on the social, political, economic and international effects of nuclear power before the first license for a nuclear plant is granted will be modified to stipulate before the first "competitive" plant is licensed. Licenses for "unproven" plants will be permitted immediately.

Nichols must assume at least a share of the blame if the proposals are caught in the logjam of legislation that Congress is sure to face at the end of this session.

The legislative proposals that Congress had requested for early January did not arrive until mid-February. Likewise, other reports, such as the five-year reactor program, were behind schedule.

Furthermore, when the legislative proposals did come to the Joint Congressional Committee, they were considered inadequate for presentation even as a bill for discussion. The Committee spent precious weeks putting them in shape for public presentation. Public hearings that had once been expected to begin in early March were not actually started until mid-May. Congressional sources placed a large share of the blame for this delay right at the AEC doorstep.

Organization

At Nichols' direction, AEC is shaping up as a true pyramid. Top staff positions, long-vacant, are being filled. Probably for the first time since AEC was chartered, there are three assistant general managers to keep a close eye on operational policy. Previously there had been an assistant manager in charge of administration, but the manufacturing post, as well as the one for research and industrial development, had gone vacant.

Still missing from near the top of the pyramid is a deputy general manager—a position vacant since veteran Walter J. Williams resigned in January. With all the assistant general manager posts filled, it is doubtful whether a deputy will be needed.

Several top men have moved out, giving the new general manager a somewhat freer hand in filling top positions. Besides Williams, William L. Davidson of the office of industrial development has returned to private business, and Carroll L. Tyler has retired as manager of AEC's Santa Fe operations office.

Robert P. Petersen, chief of the industrial and production reactor branch, is leaving in June. Other top resignations include those of Walter F. Colby, who was director of the office of intelligence, and L. E. Johnston, manager of Idaho operations.

Although there may be an exception here and there, it is not generally believed that the new Strauss-Nichols regime is responsible for the resignations of some top people.

One official who was in the process of leaving some months ago described his feelings this way, "Sure, I've had attractive offers from industry before, but since I was fairly well satisfied here, I stayed. Now with the natural transition from an old to a new administration there is the usual uncertainty about policy and organization. Faced with this, there is more incentive to make the move to outside industry."

In all there have been more than a dozen shifts in the top AEC echelon—most of these being promotions toward filling long-vacant positions or to replace men who have left.

There also have been several functional changes in organization that AEC spokesmen describe as tidying-up operations. These include the shift of feed materials production responsibilities from New York to Oak Ridge, reduction of the San Francisco office from an operations to a field office, and cancellation of research contracts with California Research and Development Corp. at the Livermore site.

On the other side of the coin, a new Army reactors branch has been created, although thus far it is a comparatively minor operation. There is no indication that Nichols' Army background had any undue influence on this move. The Army branch is an outgrowth of a year-long study on military package power reactors that is now moving into the construction stage.

This transition is necessarily slow-moving. Until it jells, there are breaks and question-marks in the chain of command. Division directors who have been accustomed to reporting to the general manager are finding their ways to the doors of assistant general managers, but below the director level the top shifts are little noticed.

What is bothering some lower-level bosses is that under the Nichols regime they no longer have direct access to Commission members. It was formerly an oft-enjoyed prerogative of a branch chief to carry his pet idea directly to some member of the five-man Commission for at least a plea of top-level action.

With a stricter chain-of-command policy, the ideas must move along the bureaucratic pattern from employee to section chief to branch chief to director to assistant general manager to the general manager—and finally, if basic policy is involved, to formal presentation to the Commission.

Complaints are heard that the process is so slow and unwieldly that an idea gets fuzzy or worn out before it ever gets active consideration at the top.

But division directors report that it is easier to get a decision on day-to-day operations than formerly. While access to the general manager is severely restricted, enough authority has been delegated downward to permit decisions on all but major policy matters.

In time, when the kinks are worked out, there is a possibility that responsibility will be fixed more squarely at lower levels—thus compensating to some extent the limited access to the general manager and individual commissioners.

Security vs. Information

Strauss likes to point to the 2 or 3-ft shelf of AEC technical publications that are available to the public. "These are all publications of the Commission," he will tell a caller, "and most people seem to think that we don't publish anything."

On few subjects is Strauss as sensitive as on security and information matters. He thinks he is unjustly accused of exaggerated security requirements. Informally he describes his position as being for "less restrictions in fields where they are not needed and for more in the sensitive field of military applications."

But when called on to make a formal declaration on security matters, he takes a negative approach: "Many years of association with the problem have shown me that when the error is on the side of too much security, that can be rectified; but if the error has been in the other direction, there is nothing appropriate but hand wringing and vain regrets."

Strauss' personal view on this subject becomes of extreme importance because Eisenhower has designated him as the government's chief censor on atomic information and news.

General Manager Nichols comes in when the Strauss views are translated into action, which is most noticeable in the field of public information.

Thus you have both Strauss and Nichols giving silent consent to this explanation of AEC public information duties by one of their subordinates: "It may be keeping [a story] out of the paper. That is part of this job too."

To turn AEC information into a news release, at least two clearances are required. First, the information must be passed by the office of classification; this assures that security is not involved. Second, and this is where criticism is most prevalent, the

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release must be cleared by the Office of Public Information to make sure it is in line with administrative policy.

Take this example. Some nine industrial firms made broad-scale bids in February of this year to participate in the PWR project. Because of the intense interest in this award, the reactor division proposed a news release on the opening of these bids outlining the number and scope of the bids received.

No question of security arose, but when the proposed release was taken to the general manager's office for administrative clearance, it received an immediate turn-down. Queries by the Joint Congressional Committee failed to bring this information into the public domain.

However, when a Senate appropriations committee requested the list of bidders two months later, it was furnished by Nichols with no questions asked.

When Strauss first took over last July, newsmen thought they noticed a gradual clampdown on news coming out of AEC. At that time Strauss denied that he had initiated any new procedures for closer screening of AEC news releases or other information activities.

Insiders explained the situation in this way: there hadn't been an actual directive calling for closer control. It might be that the Strauss reputation for tight security was having effect on information men down the line who were trying to anticipate his wishes.

Since then there have been actual directives that give Nichols and Strauss a tighter control over news out of AEC.

The first was issued last fall to AEC field information men. It called for Washington clearance of all but the most routine press announcements. This directive stirred something of an uproar when field information men held their annual meeting last year. Outcome was that a manual was supposed to be drawn up for handling information and other administrative matters.

Second, and a potentially more far-reaching directive was circulated to most AEC employees in March of this year. This covered relations of AEC staff members with newsmen. In the bureaucratic style, it started off "You will . . ." and went on to say that all queries from newsmen would be referred either to Public Information, the General Manager, or the Commission.

The Congressional Joint Committee also took a look at this directive. There is a vague understanding among Committee sources that this directive is, for the present, inoperative. However, as far as could be determined, Nichols took no immediate steps to circulate a second directive modifying or softening the earlier one.

In contrast to these restrictions on day-to-day release of news and sharing of public information, Strauss is on record as favoring a much broader dissemination of technical information to industry and to friendly foreign nations.

He is supporting changes in the 1946 Atomic Energy Act that would make it possible to share limited defense information and a broad area of power reactor information with foreign countries.

To explain this apparent conflict, Strauss' admirers argue that he is intent on carrying out present law to the letter. If that law is relaxed they think Strauss will welcome a chance to let down bars on all but the sensitive weapon information.

Sidelights

Republic Steel to study applications. Robert P. Petersen, chief of the industrial and production reactors branch of AEC's division of reactor development, will join Republic Steel Corporation on July 1 to study and develop means of using nuclear energy in the steel industry.

•

Dow-Edison work enters test stage. AEC has approved Dow-Edison group's (26 project companies) plan to perform experiments and preliminary engineering toward development of a breeder power reactor. The companies will spend $2.3-million this year. Research at AEC facilities will entail $300,000 of this. The government will spend an equal amount on work of direct interest to AEC.

•

Purdue plans two-week radiochemistry course. Industrial applications of atomic energy will be covered in a lecture-demonstration-laboratory course to be presented at Purdue University July 12–23. Basic principles, experiment design, and instrumentation also will be covered.

•

Harwell starts its fourth reactor. A small, heavy-water, high-flux reactor being built at Harwell will provide for power reactor experimental studies.

World's A-Power Potential Reported to Congress

Probable status of nuclear power in foreign countries during the next 20 years is considered in a report recently submitted to Congress by AEC.

Prepared by the State Department at the direction of the Atomic Energy Commission, the report says that nuclear power plants will not automatically usher in a new era of plenty and rapid economic growth in the nations of the free world. Rather, the report takes the view that here is a promising new energy source that must take its place in competition with existing sources.

The report was prepared for inclusion in AEC's informal study of the broad economic, social, and international implications of nuclear power development. Under section 7b of the Atomic Energy Act such a study is required "whenever (in AEC's opinion) any industrial, commercial or other nonmilitary use of fissionable material or atomic energy has been sufficiently developed to be of practical value."

The Joint Congressional Committee on Atomic Energy last year asked AEC to compile an informal study along these lines for guidance in amending the act to permit industrial development of nuclear power.

In attempting to gage the nuclear power potential in foreign countries, the report is limited to a 20-year outlook, with case studies in five industrial nations. It assumes that nuclear power plants will be available early in the period 1960–1975 in a reasonably flexible array of sizes. Investment costs will run around $75/kw above costs of conventional steam or internal combustion plants. If allowed to operate 80% of the time, these nuclear plants will be capable of producing 7–8-mill power.

Here are highlights of the report:

- Nuclear power plants will be competitive with conventional plants using high-cost coal or oil.
- They can't compete with existing

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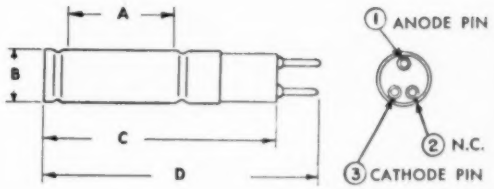

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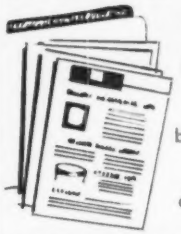

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hydroelectric generation or with future hydropower developed at favorable sites.

• Even where nuclear plants produce cheaper energy, they won't be a major stimulus to economic growth. Power costs are only a small part of the operating costs of most industries. Investment incentive and sound business management will retain their essential roles.

• Highly industrialized countries with dwindling low-cost energy sources are most likely spots for nuclear power development. Great Britain and Japan are good examples.

• Except in special cases, nuclear power is likely to be less economical than conventional power sources in the less-developed areas.

• Some countries will go ahead with nuclear power projects, even though uneconomic, for reasons of national prestige, or to conserve scarce foreign exchange.

Only cost advantage that nuclear plants offer over conventional power plants is in the fuel. The reactor will be more expensive than the boiler for conventional coal or oil plants. Cost of turbines, generators, switchgear and transmission facilities will be almost equal in cost.

Since the fuel cost of operating a modern electric generating plant runs only about one-third of the total production cost, the area of savings is limited. Cost of nuclear fuel will be just a shade below 3 mills/kwh.

All but about 16% of the modern steam plants in the U. S. are now beating the 7-8-mill production cost predicted for nuclear power during the next decade or two.

Thing to remember is that the U. S. is one of the favored nations in the generation of electricity. Besides sizable hydroelectric resources, this country also has plentiful supplies of coal and oil.

Its a different story in other nations.

Great Britain. Continually rising costs of coal in Britain will likely render nuclear-generated power competitive with conventional sources by 1960. During the next 15 years, this new source of power could economically spread through most of the country.

Current costs of generating electric power at steam plants in Britain average 8.2 mills/kwh. However, there is a wide variance in production costs because of differences in plant efficiency and fuel and delivery costs.

These differences may be offset somewhat by locating more plants at pitheads and the integration of power into the super grid now under construction. But even with these advantages, the rising cost of coal will boost power costs to around 11 mills/kwh during the next 20 years.

If half of new capacity additions beginning in the mid-1960's are nuclear powered, approximately one-fifth of total generating capacity would be nuclear powered by 1975. On this basis, assuming nuclear power at a cost of 7 mills/kwh, there would be a total saving of around $136-million annually over coal-powered plants.

Japan. This is another industrial nation with dwindling conventional fuel resources. It has tapped most of its favorable hydropower sites, which now furnish about 80% of the nation's electric power requirements. Domestic coal, for the most part low-grade and high-cost, furnishes most of the remaining 20%.

Best figures available indicate the power produced at Japanese steam plants runs around 20 mills/kwh.

Thus nuclear power will be able to compete with some 20% of Japan's power generation whenever the new power source can be efficiently developed at something below 20-mills.

Biggest barrier to nuclear power development in Japan is the lack of any concerted research or development program. Some basic research is underway, but it has not advanced to the stage of power reactors.

Economically the adoption of nuclear power in Japan depends mainly on access to nuclear fuels at cheaper costs than equivalent conventional fuels, and on being able to secure manufacturing rights to nuclear power reactors and auxiliary equipment.

Brazil. Bulk of Brazil's electric power requirements for the next 20 years can be more economically met from hydropower than from nuclear power. The hydro potential is the largest in South America and ranks very high in the world. Cost of hydro production is considerably below the 7-8-mill/kwh cost assumed for nuclear power.

There may be room for some nuclear power development to replace thermal plants. However, this would come mainly in remote areas where inland resources are being developed. Even there, domestic oil might serve the purpose better because plants would seldom run at full capacity. Nuclear plants with higher fixed costs would be hard put to compete with conven-

tional plants with access to cheap fuel.

The financial situation adds another dimension to the nuclear power picture in Brazil. Because there is ample opportunity for high-return speculative activities, little attention has been given to electric utility investment in the country. This is one of the main reasons for the current power shortage.

Nuclear power, with its higher initial investment requirements, would be in a poor competitive position with conventional thermal generation.

Northern and Southern Rhodesia. Although the Rhodesias have huge potential deposits of nuclear fuel ores, there is little reason to believe it will turn to nuclear power to solve its present energy shortages.

Reasons are that it still has ample resources of hydropower and coal, both of which can beat the assumed costs of nuclear power.

Like Brazil, the Rhodesian power shortages arise from failure to attract investment in electric utility operations. Nuclear power would be no solution to that problem.

Thus it seems a good bet that Northern and Southern Rhodesia will export their uranium ores while they exploit their cheap hydro and coal resources for domestic power.

9 Groups Offered to Build, Operate PWR

Nine electric companies and industry groups offered to join with the Atomic Energy Commission in building and operating the first utility-size atomic power plant in this country.

Full list of bidders was disclosed recently although the Duquesne Light Co. offer had been accepted more than a month earlier (NU, April '54, p. 78). This plant is now in the design stage at Westinghouse Electric Corp. and will be erected on land furnished by Duquesne Light near Pittsburgh. AEC Chairman Lewis Strauss has estimated the Duquesne offer, which includes a $5-million contribution to design and construction as well as assuming operation of the full plant, will save the government some $30-million.

Besides Duquesne Light, the following eight firms and groups also offered "broad scale" participation in the large-scale atomic power plant project: 1. Cisco Construction Co., Portland, Ore.; 2. Connecticut Light and Power Co., Berlin, Conn.; 3. Consumers Public Power District, Columbus, Neb.; 4. Eastern Utilities Association, Bos-

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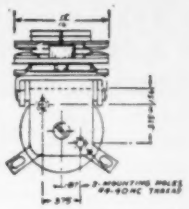
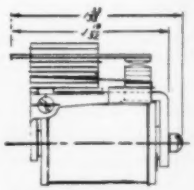


END VIEW



SIDE VIEW

Among the wide variety of *Standard* Phil-Trol Relays you will find many designed to solve your "special" problems . . . like the types 4BQA and 4BQA POWER shown above. While both are small, compact, lightweight units, each is designed to perform its job best. For example:

The 4BQA Multi-contact D.C. is used where very sensitive or marginal operate and release factors are required. This relay may be provided in multi-contact combinations with as many as 12 contacts.

The 4BQA Power Type D.C. has the capacity to handle large currents on the contacts. Standard contacts are rated at 25 amperes.

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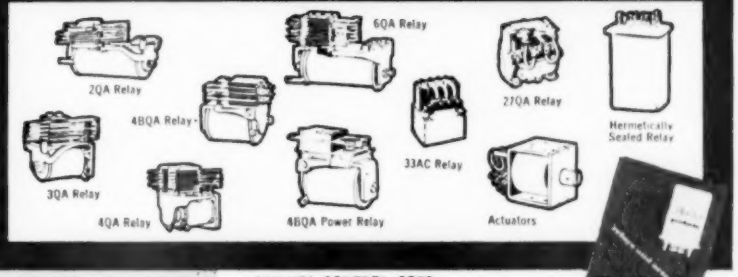

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K-700 Pocket Chamber
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ton, Mass.; 5. Middle South Utilities, Inc. and Ebasco Services, Inc., New York City; 6. Nuclear Power Group: American Gas and Electric Service Corp. of New York; Bechtel Corp. and Pacific Gas and Electric Co. of San Francisco; Commonwealth Edison Co. of Chicago; and Union Electric Co. of St. Louis, Mo.; 7. Philadelphia Electric Co. of Philadelphia and Pennsylvania Power and Light Co. of Allentown, Pa.; 8. South Carolina Electric and Gas Co. of Columbia, S. C.

In addition, offers were received from the following for "very limited" participation: Infilco, Inc. of Tucson, Ariz.; cities of Lenoir and Morganton, N. C.; R. B. MacKenna of Santa Fe, N. M.; Reynolds Metals Co. of Richmond, Va.; Sylvania Electric Products, Inc. of Bayside, N. Y.

Pratt & Whitney Aircraft To Step Up A-Plane Work

Air Force and AEC have requested funds from Congress to increase aircraft reactor activities of Pratt & Whitney Aircraft Division, United Aircraft Corp.

A government-owned research, development, and test facility is planned. This Hartford Research Facility, located in Connecticut, will be operated by Pratt & Whitney. The Air Force has asked $5.75-million for the project.

AEC has asked for $8.6-million to continue joint ORNL-P&W work. Oak Ridge National Laboratory is also the center of nuclear and shielding research for all contractors in the aircraft reactor program.

General Electric's group at Lockland, Ohio, is slated to get $5.6-million from AEC for a different approach to aircraft reactor development. GE also has an Air Force contract for work on other propulsion system components.

What Will AEC Funds Be Used for in 1955?

The Atomic Energy Commission has asked Congress for $1.352-million for fiscal 1955. The greatest part of this money will go into the weapons program, gaseous-diffusion plants at Portsmouth, O., Paducah, Ky., and Oak Ridge, Tenn., and the production reactors at Savannah River and Hanford (NU, May '54, p. 75). Here is a breakdown of unclassified expenditures of particular interest to readers of NUCLEONICS.

Fissionable materials. $1.6-million requested for changes and additions to existing feed materials plants; $10-million for a fabrication plant for reactor fuel elements; $15-million for a production plant for special products; $105-million for expanded gaseous diffusion facilities at Oak Ridge; $5.5-million for changes in fissionable material recovery plant at Oak Ridge; $6-million for a tank farm for radioactive wastes at Hanford, requiring pumping stations and tie lines to existing tanks; $97.9-million for changes and additions to production facilities at Hanford; and $1.5-million for similar work at Savannah River.

Reactor program operating costs. At AEC-owned facilities: $13.5-million for research and development work at KAPL (GE) and $4-million for operation of SIR (including fuel preparation); $12.6-million for work at ORNL (Carbide); $9.7-million for work at ANL (U. of Chicago); $9.8-million for research and development at Bettis (Westinghouse) and $5.3-million for operation of STR, including fuel preparation; $9.1-million for National Reactor Testing Station (Phillips); $5.6-million for Livermore (U. of Cal.); $1.7-million for Brookhaven; $900,000 for UCRL; and $250,000 for Ames.

At non-AEC-owned facilities: $705,000 for Battelle; $272,500 for Brush Beryllium Co.; $5.5-million for GE (Lockland); $565,000 for MIT; $3.7-million for North American; $555,000 for Sylvania; and $1.5-million for Pratt & Whitney.

Industrial reactors. Appropriations for the industrial power reactor program were detailed in last month's NUCLEONICS (pp. 72, 76).

Advanced reactor engineering development. $702,000 requested for reactor design and evaluation. This activity creates and evaluates new reactor designs through stages of preliminary design and feasibility report. Effort is primarily at ANL, ORNL, BNL, and MIT. $1,16-million requested for reactor physics and critical assembly work (ANL, BNL, and KAPL); $1.9-million for reactor fuel-systems development (ANL); $2.8-million for development of new reactor materials and components (ANL, KAPL, ORNL, NAA, MIT, etc.); $716,000 for development of improved coolants and heat transfer and power generation equipment and systems (ANL); $380,000 for improved instrumentation and controls (ANL); $665,000 for shield development (ORNL, BNL, etc.); $2.6-million for improved separations systems (ANL, KAPL,

ORNL); $400,000 for waste treatment systems (ANL, BNL, KAPL, ORNL); and $825,000 for sanitary engineering (U. S. Weather Bureau, Public Health Service, Geological Survey, etc.).

Service facilities. $2.4-million requested for operation of materials testing reactor, $3.94-million for operation of chemical processing plant. $4.4-million requested for operation of experimental reactors, test facilities, and modifications to reactors; $10.6-million for operation of processing plants.

$2.7-Million Research Reactor Planned for ORNL

It is expected that a 10-Mw, high-flux research reactor soon will be built at Oak Ridge National Laboratory. The unit, to use enriched-uranium as fuel and light water as moderator and coolant, will be suitable both for fundamental research and for engineering studies of radiation damage.

Design has been completed at a cost of $100,000; construction of the reactor, its building, and auxiliary facilities is expected to involve $2.7-million. Funds have been requested in the '55 budget.

Divided Shield Gives Lighter A-Plane Shield

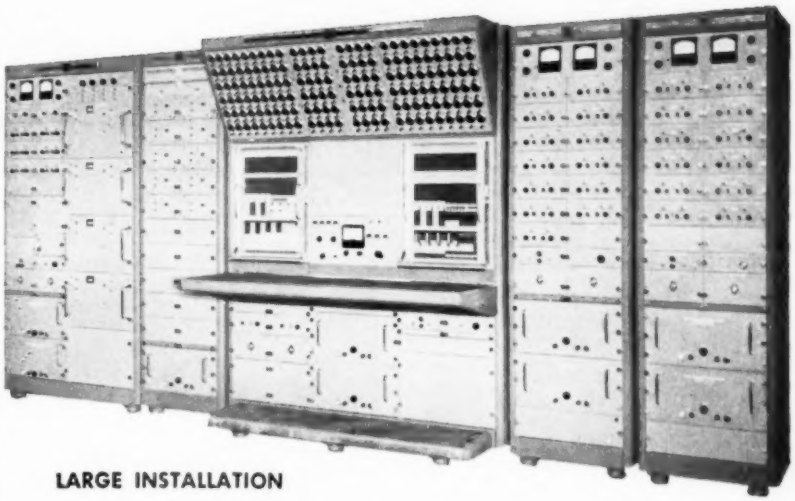
Lighter total shield weight can be obtained on a nuclear-powered airplane by shielding the reactor partially instead of fully and by placing the rest of the shield around the crew at a compact flight station.

According to H. L. Hibbard of Lockheed Aircraft Corp. a proper compromise must be reached between reactor and crew shields. Type of reactor and heat transfer system and effects on airplane service and maintenance also must be considered.

MEETINGS

June 20-25: American Institute of Chemical Engineers' International Nuclear Engineering Congress; University of Michigan, Ann Arbor, Mich. Over 90 papers will be presented on power, research, and educational reactors; reactor materials, technology, and fuel refining and preparation; and applications and uses of radioactive products. Discussions will be held on nuclear education, social effects, and journalism. Equipment will be displayed. Obtain information from R. R. White, 2028 East Engineering Bldg., University of Michigan, Ann Arbor, Michigan.

MODERN Problems Demand ... MODERN SOLUTIONS



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This large computer is used for the rapid solution of aero-dynamic problems. It consists of 50 operational amplifiers, 10 servo multiplying channels, 4 resolving channels, and a control console with two pre-patch bays, 156 attenuators, two voltmeters, and all necessary operational controls.

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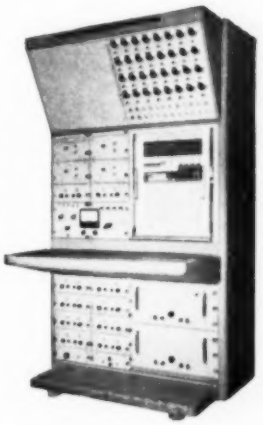
Our Type 16-31R Computer is a single package computer capable of solving differential equations with many simultaneous elements which are often encountered in the simulation of dynamic systems. It contains 20 operational amplifiers, 4 servo multipliers, thirty-two attenuators, all-metal removable problem board, and complete control panel.



PLOTTING EQUIPMENT

For presentation of problem solutions, the Variplotter Plotting Boards provide an accurate inked record. Typical uses include the automatic plotting of: Analog Computer output; guided missile data; engine performance characteristics; and control of manufacturing processes. With accessory equipment the range of applications can be greatly extended.

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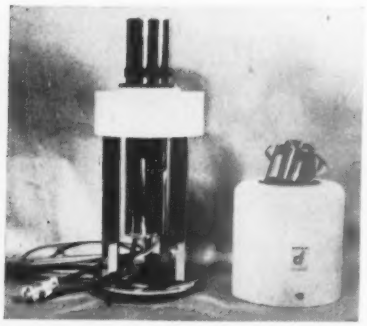
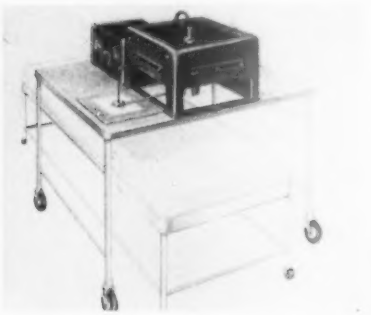


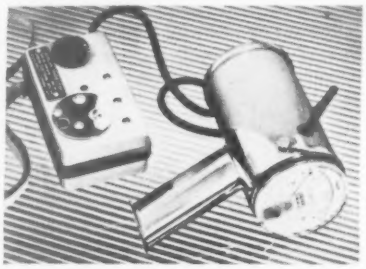
Scintillation Counter

The model DP4 well-type scintillation counter is supplied with a sodium iodide crystal in a probe assembly that can also be used separately. The probe accepts any type of crystal. The counter utilizes a Dumont 6292 photomultiplier tube with a 6AK5 cathode follower. The tube is shielded with 2 in. of virgin lead finished in baked-on white enamel for easy decontamination. All metal parts of the probe are finished in hard chrome. *Detectolab, Inc., 6544 N. Sheridan Rd., Chicago 26, Ill.* (P-1)



Isotope Scanner and Recorder

The Tracer-Scanner is an instrument for scanning body areas and producing a graph of isotope concentration, and is particularly useful for showing iodine-131 distribution in the thyroid gland. Equipment includes a collimated scintillation detector; motorized mount for detector to provide for vertical movement; scanning device to move the detector over portion of body being scanned; scaler and power supply for detector; printing device to record radioactivity distribution; and wheeled table to carry the equipment, which is designed to straddle hospital bed or examination table. Scanning area is 15 × 15 in.; scanning speed is adjustable. Solenoid-operated recorder produces a $\frac{1}{8}$-in.-long line each time it is actuated, and prints on tracing paper backed with carbon paper to provide direct-reading image and several copies. *Tracerlab Inc., 130 High St., Boston 10, Mass.* (P-2)

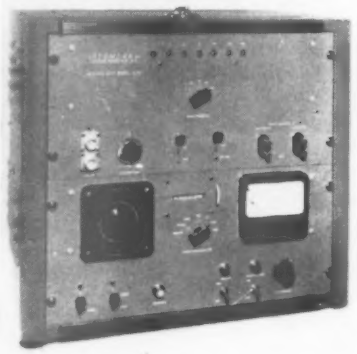


Beta-Gamma Detector

The model AGB-10-SR ionization-type beta-gamma survey instrument can detect increments in radiation as small as 0.002 mr/hr above background. Logarithmic response permits readings from 0.01 mr/hr to 10,000 mr/hr in three ranges at an accuracy of 10%. Control unit contains mercury batteries for 350-hr continuous use and calibrated source. *Jordan Electronic Mfg. Co., Inc., 119 Union St., Pasadena 1, Calif.* (P-3)

Preset Counter

This dual preset counter provides output information at any two counts; any discrete physical change, represented by a changing voltage, can be counted. Response of the unit is from d-c to 40,000 cps, maximum continuous rate. *Beckman Instruments, Inc., 2200 Wright Ave., Richmond, Calif.* (P-4)



Binary Scaling Unit

The model A-72 scaling unit was designed for Geiger, scintillation and proportional counting, and has a 1-mv sensitivity and plug-in scaling units with resolution of 2 μsec. Provision is made for counting-rate meter operation. The unit has a flat frequency response up to 1.5 Mc and input attenuation ratios of 10:1, 3:1 and 1:1. Other features are: regulated high-voltage supply; scale of 128; built-in timer for predetermined time operation; and predetermined count from 10 to 12.8 × 10^6 counts in 25 steps. *The Atomic Center For Instruments & Equipment, Inc., 489 Fifth Ave., New York 17, N. Y.* (P-5)

Amplifier, Preamplifier

The model 218 linear amplifier provides maximum high-level output of +90 volts and maximum low-level output of +2.5 volts. Controls include coarse and fine gain, bandwidth switch (2.0, 0.5, and 0.1 Mc), and pulse-height selector. Ten-turn helical potentiometer provides control of pulse height discriminator at high-level output. Used with the amplifier, model 219 preamplifier provides added gain for high-impedance low-level-radiation detectors; gain is 30 and rise time <0.2

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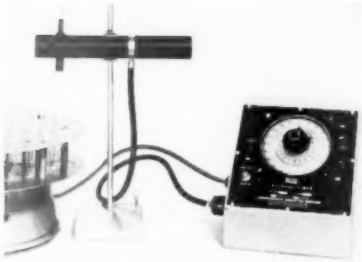
μsec. Separate transformer supplies filament voltage to preamplifier. Overload response is said to be good enough to allow taking scintillation spectra in the 22-kev range in the presence of 75-Mev background with little or no distortion. *Atomic Instrument Co., 84 Massachusetts Ave., Cambridge 39, Mass.* (P-6)

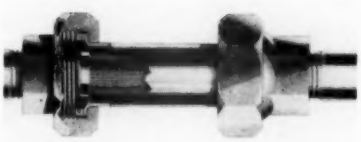


Drop Counter

This drop counter has a photoelectric cell connected to a timer and counts 1–400 drops. Drops fall directly from a glass tip into collecting tube without touching any part of counter assembly. Timer automatically indexes collector to next position after preset number of drops have been delivered. *Microchemical Specialties Co., 1834 University Ave., Berkeley 3, Calif.* (P-7)

Linear Amplifier

The model 107P nonoverloading linear amplifier has a sensitivity of 0.1 mv to 100 v and accepts either positive or negative pulses. The amplifier has a rise time of 0.2 μsec and a gain of approximately 40,000, continuously variable. It supplies a positive output that exceeds 80 volts and has a continuously variable clipping time from 0.2 to 50 μsec. The 107P has a self-contained power supply; the pulse-height selector is a trigger-type high-resolution integral discriminator based on Bell-Jordan design. *Radiation Instrument Co., Box 733, Silver Spring, Md.* (P-8)

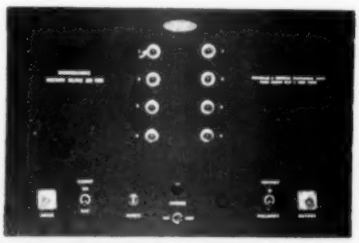


Strainer

The Straightflo strainer, designed to eliminate unnecessary friction, loss, and turbulence, provides an uninterrupted flow of water, air or gas. The straight-line design is said to give large cleaning area with infrequent strainer cleaning. Strainer is installed with union couplings. All parts are claimed to be noncorrosive. It is available in $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{3}{4}$, and 1 in. pipe sizes. *Hays Mfg. Co., 814 W. 12th St., Erie, Pa.* (P-9)

Radiochemicals

A variety of S^{35}, C^{14} and P^{32} labeled radiochemicals are available from stock or on special order. *Schwarz Laboratories, Inc., 230 Washington St., Mount Vernon, N. Y.* (P-10)

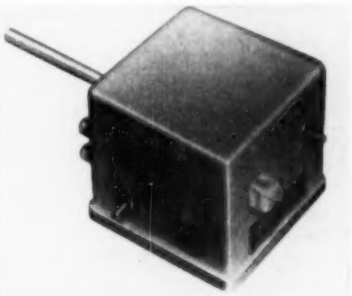


Decade Scaler

The model 412 fast decade scaler has been designed for high-speed counting of fast pulses encountered in nuclear work. Resolving time is 0.1 μsec; maximum continuous counting rate is 10^7 cps. The 412 has a decade scale of 100 and a 1-2-4-8 indication system for each of two decades. *Electrical and Physical Instrument Corp., 42-19 27th St., Long Island City, N. Y.* (P-11)

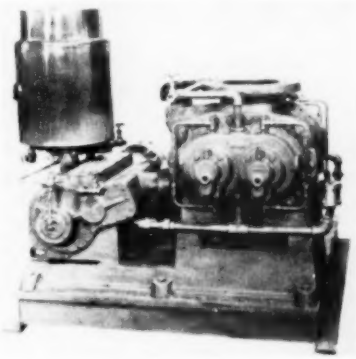
Eye-Probe Counter Tube

The model 225 eye probe is an alpha and beta counter tube with a 60-deg bend that permits its use behind the eye. Used to locate small active areas, probe detects fractions of microcuries of I^{131} and P^{32}. The neon-halogen filled probe is claimed not to be damaged by overvoltage nor affected by temperature changes in the range −55° to 100° C. At the operating voltage of 600–650 volts and shielded by $\frac{1}{4}$ in. Al + 2 in. Pb, background is 10 cpm, maximum. The $\frac{3}{16}$-in.-diameter mica window is 1.4–2 mg/cm². *Anton Electronic Laboratories, Inc., 1226–1238 Flushing Ave., Brooklyn 37, N. Y.* (P-12)



Relay Control Box

This electronic relay control box was designed for applications such as controlling motors, constant temperature baths, and ovens. The relay has a total load capacity of 1,500 watts; its control circuit requires 5 μa for operation. It contains an isolating transformer, a 2D21 vacuum tube, a heavy duty relay and a two-position switch that puts the relay in a normally open or normally closed position without rewiring. *Labline Inc., 217–221 N. Desplaines St., Chicago 6, Ill.* (P-13)



Booster Vacuum Pump

The model MB mechanical booster vacuum pump is designed for use as a

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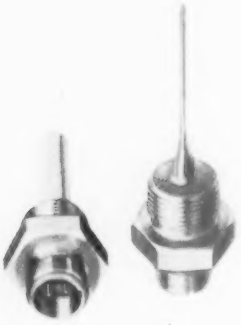
high-vacuum stage in the low-pressure range where single-stage vacuum pumps have poor volumetric efficiency. Since no sealing fluid is required, the booster acts as a positive displacement compressor to retard backstreaming of oil vapors into the vacuum system. The model MB 1200, with the Kinney single-stage 125-ft³ pump, has pumping speed of 750-ft³/min at 1-micron pressure and about 1,000 ft³/min at 10 microns to 1 mm Hg. Combined unit requires 5 hp at high vacuum and 15 hp at 15 mm Hg. *New York Air Brake Co., Kinney Mfg. Div., Boston, Mass.* (P-14)

Solvent-Proof Paint

A strip coating can be produced when Varniton solvent-proof paint is coated on glass or smooth metal surfaces. Decontamination of table areas, etc. can then be made when solvents spill on this surface. At least four coats must be applied to form a film thick enough for stripping. This paint was designed to protect surfaces from organic solvents, fumes, light, heat, water and inorganic chemicals. *The Varniton Co., 416 N. Varney St., Burbank, Calif.* (P-15)



Temperature Detector

The model 221 N90A hermetically sealed, electrical-resistance-type detector is designed for use with temperature recording, indicating and control equipment where fast response is a primary requirement. It has an exponential time-constant of 0.8 sec or better in an agitated water bath. Its useful temperature range is −70° C to +200° C. Accuracy is ±1% or better in the mid-scale region. The sensing element is a nickel winding with a resistance of 90.38 ohms at 0° C. *Thomas A. Edison, Inc., West Orange, N. J.* (P-16)

D-c Magnetic Amplifier

The type 806 low-level d-c magnetic amplifier operates with input signals down to 200 μμw with a power gain of approximately 300,000. With the proper input, the amplifier can deliver an output of 0.05 watts, reversible polarity, to a 50-ohm load. The unit is self-contained. Two feedback windings are provided for external connections. *Polytechnic Research & Development Co., Inc., 55 Johnson St., Brooklyn, N. Y.* (P-17)

Level Indicator

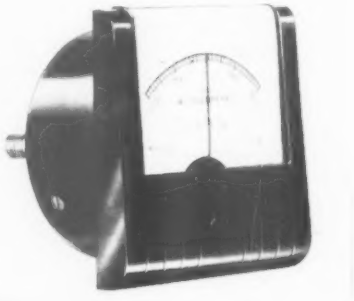
This level indicator has a differential converter that utilizes a pneumatic balance weigh-beam system to convert differential pressure to proportionate air pressure to measure the level of liquids in a closed tank under pressure or vacuum. The range is adjustable from 0–14 to 0–200 in. of water. The instrument operates at up to 350° F and is rated for pressures of 750 or 1,500 lb in.² *Minneapolis-Honeywell Regulator Co., Wayne & Windrim Aves., Philadelphia 44, Pa.* (P-18)

Vacuum Tube Voltmeter

The type A vacuum tube voltmeter requires the same panel area as a standard 3½-in. meter and has depth of 4¼ in. Available full-scale sensitivities are 10 mv, rms, to 300 volts, rms. With input impedance of 1 megohm and accuracy of 3%, meter can be used for measurements of 20–50,000 cps. Type A does not include power supply; other models include supply. *Trio Laboratories, Box 143, Wantagh, N. Y.* (P-19)

Four-Way Valve

This 4-way valve is hand-and-foot operated with patented built-in, full-capacity, flow-control meters of the venturi type. It is designed for controlling double-acting air or hydraulic cylinders. The basic valve is also available for remote pilot, cam, single- or double-solenoid time-delay operation. *Airmatic Valve, Inc., 7317 Associate Ave., Cleveland 9, Ohio.* (P-20)



Electricity Meters

The model 721 2½ in. square semiflush instrument has a molded Plexiglass front case that can be furnished clear to view the instrument movement. The instrument is available with d-c or a-c movement, and as rectifier-type instrument, for VU and db indicators and a-c voltmeter. Thermocouple rf milliammeter utilizing an internal thermocouple is available in same model. *Burlington Instrument Co., 151 N. Third St., Burlington, Iowa.* (P-21)

Vacuum-Sealed Resistors

The Welmeg resistors were developed for use in nuclear research and other development work, and are most suitable for use with electrometer tubes, ionization chambers and other applications where high-resistance values are required with close tolerance and good stability. These vacuum-sealed resistors are available in values from 5×10^7 to 10^{12} ohms at ±1 to ±20% tolerances. Their stability is said to be better than 2% annum at room

temperature, and >5%/month at 100° C. *Rockbar Corp., 215 E. 37th St., New York 16, N. Y.* (P-22)

Two-Way Solenoid Valves

The Special 8268 and 8269 two-way solenoid valves handle corrosive gases and liquids, as well as steam, up to 450° F. The 8269 is equipped with an explosion-proof solenoid. Bodies are steel or stainless steel. The packless-type valves have beveled stainless steel regrindable or replaceable disks. Valves are normally closed; normally open valves may be ordered. Laminated or solid cores are available. Pipe sizes are $\frac{3}{8}$ and $\frac{1}{2}$ in.; orifice diameters are $\frac{1}{8}$–$\frac{3}{8}$ in. *Automatic Switch Co., 391 Lakeside Ave., Orange, N. J.* (P-23)

Dual Cathode Follower

The type M1523 dual-type cathode follower utilizes the characteristics of the 5687 tube to provide two independent cathode followers within a

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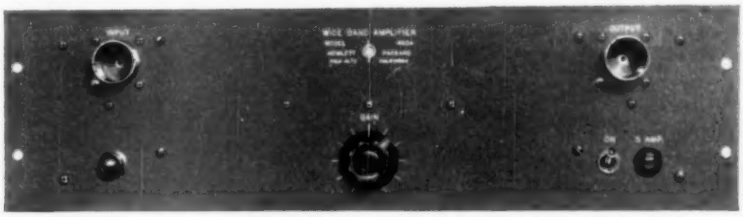
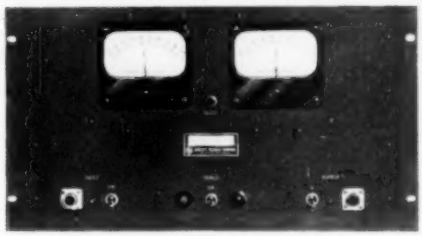


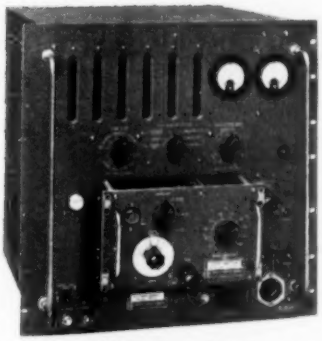
-*hp*- 460A Wide Band Amplifier

-*hp*- 46A Connectors

-*hp*- 520A High Speed Scaler



-*hp*- 410B Vacuum Tube Voltmeter



-*hp*- 524B Electronic Counter

-*hp*- 460 series Amplifiers give you up to 90 db gain in cascade, true amplification of millimicrosecond pulses, 0.0026 microsecond rise time, 125 volt open circuit output and 100 megacycles bandwidth for standard oscilloscopes. -*hp*- 520A High Speed Scaler is an aperiodic instrument for precision period pulse counting from 0 cps to 10 mc. Its double-pulse resolving time is 0.1 μsec, triple-pulse resolving time 0.2 μsec. -*hp*- also offers a complete line of electronic counters, oscillators, voltmeters, VHF, UHF and SHF signal generators and other equipment for nuclear radiation, television or similar work.

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single unit for coupling low output impedances with high input impedances. The input grids are provided with 100k resistors, which may be connected to an external bias source or left floating so that the input can be directly coupled, utilizing the high-impedance characteristic of the cathode follower. Each cathode output impedance is 100 ohms, tapped at 1,000 ohms, with the signal amplitude at the tap approximately 65% of the cathode-signal amplitude. An output impedance of approximately 50 ohms is available by paralleling the two sections. *Walkirt Co., 145 W. Hazel St., Inglewood, Calif.* (P-24)

Differential Analyzer

The CRC-105 decimal digital differential analyzer solves problems in the form of an ordinary differential equation and some partial differential equations. The decimal system, together with initial condition storage, is said to cut filling time 75% over analyzers using binary system. System utilizes 60 integrators with maximum accuracy of 6 digits and sign in each integrator; 60 increments of the independent variable are computed per second. Twelve input and twelve output channels are synchronized within the machine. Input-output media include automatic typewriter and graph plotter. *Computer Research Corp., 3348 W. El Segundo Blvd., Hawthorne, Calif.* (P-25)

Nickel-Silver Strip

Custom-rolled 18% nickel-silver strip is available up to 6 in. wide and to 0.0005 in., to tolerances of ±0.0001 in. The metal is malleable and ductile and resistant to corrosion, wear, and fatigue. It may be ordered in any quantity. *American Silver Co., Inc., Industrial Div., 36-07 Prince St., Flushing 54, N. Y.* (P-26)

D-C Signal Calibrator

The Pulsescope enables instantaneous direct-reading d-c calibration of positive or negative signals. The unit has a vertical amplifier sensitivity of 0.2 volts (rms)/in. and responds from d-c to 5 Mc within 3 db, or a pulse rise of 0.1 μsec. Internal intensity-modulated markers are provided for 1, 10, 100 or 1,000 μsec. Repetitive or trigger sweep is available from 5 cycles to 500 kc with 5× sweep expansion. The Pulsescope operates at 115 volts, a-c, 50 to 400 cps. Size is $8\frac{1}{2} \times 6\frac{3}{4} \times 13\frac{3}{4}$ in. *Waterman Products Co., Philadelphia, Pa.* (P-27)

Temperature Test Chamber

The TC-2 temperature test chamber permits tests from −65° F to +350° F. A loading port at the top of the chamber permits addition of dry ice during extended operation at low temperatures. *Statham Development Corp., 12411 W. Olympic Blvd., Los Angeles 64, Calif.* (P-28)

Lyophilizing Unit

This Pyrex apparatus is designed for quick drying and freezing of organic tissues. Dimensions are 4 in., o.d., 3 in., i.d., and 300 mm long. The lyophilizing time for this unit, with its full capacity of 400 cm^3, is within 6 hr. It is furnished complete with four receiving flasks. *Wakefield Industries, Inc., 5108 W. Grove St., Skokie, Illinois.* (P-29)

Coded Receiver

This coded-signal receiver permits automatic operation of signals, relays, circuit-breakers, switches and other electromechanical devices in remote locations according to preselected programs. These receivers are controlled by code pulses transmitted over regular a-c lighting wires when used with an electronic time and program control system, and by electrical impulses when used with wired time systems. The first code pulse activates a code-selector mechanism in all receivers tuned to the frequency being transmitted and the second pulse selects those units which are to function. *International Business Machines Corp., 590 Madison Ave., New York 22, N. Y.* (P-30)

Voltage Dividers

The models 2006 and 2007 resistive voltage dividers are available for use with Keithley electrometers. Maximum inputs are 2,000 and 20,000 volts, respectively, with input impedances of 10^{12} ohms. The dividers add ranges of 200, 800, 2,000, 8,000, and 20,000 volts to the electrometers. *Keithley Instruments, 3868 Carnegie Ave., Cleveland 15, Ohio.* (P-31)

Tetrode Transistors

The types RD-X302, RD-X301, and RD-X300 grown junction tetrode transistors have maximum ratings of 30-volt collector voltage, 5-ma collector current, 50-mw collector dissipation, and 5-ma base-to-base current. Maximum

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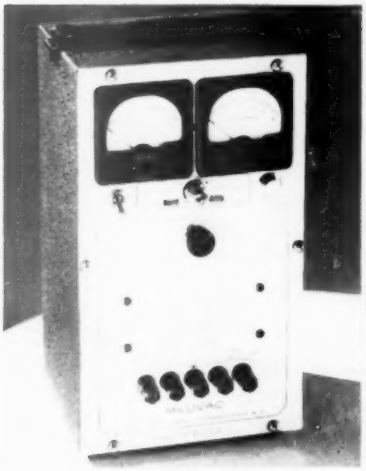
frequencies provided by oscillator circuits are 10–20 Mc, 20–35 Mc, and above 35 Mc, respectively. Maximum power gains provided by amplifier circuits at 5 Mc (input impedance, 25 ohms; output impedance, 9,000 ohms) are 12 ± 3, 14 ± 3, and 16.5 ± 3 db, respectively. *Germanium Products Corp., 26 Cornelison Ave., Jersey City, N. J.* (P-32)



Regulated D-C Power Supply

The type RP d-c power supplies are dynamically compensated to provide zero or slightly negative internal impedance to compensate for voltage drops in the power supply leads, as well as load changes and line voltage variations. An adjustment can be used to set the internal impedance of the supply positive or negative, as required. Models RP-41, 42, 43 and 44 supplies are available at normal ratings of 250 to 400 volts and 50 ma to 100 ma; each model supplies 6.3 volts a-c, 2 amperes, unregulated. *Millivac Instrument Corp., Box 997, Schenectady, N. Y.* (P-33)

Digital Electrical Meter

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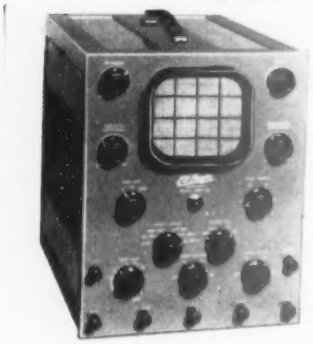
0.8-sec speed. It measures up to 10 megohms in seven ranges, 1,000 volts in six ranges and 1 ampere in six ranges. Maximum accuracies at the lower scales are ±0.01 ohm, ±0.00001 volt and ±0.01 microampere. Operation does not involve manual adjusting or balancing. The Digitester can also be used to control acceptance or rejection functions in an automatic tolerance test of components. Special models are available that operate auxiliary recording devices such as electric typewriters, card punches, and tape perforators. *Telecomputing Corp., 133 E. Santa Anita Ave., Burbank, Calif.* (P-34)

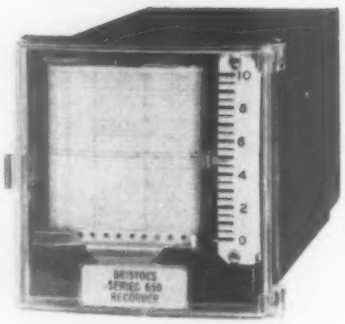


Laboratory Oscilloscope

The model WBO-50 oscilloscope is a general-purpose instrument. The vertical amplifier is essentially flat to 5 Mc ± 3 db and has a directly-calibrated vertical gain control to read peak-to-peak volts. Vertical sensitivity is 20 mv (rms) per in., 4 in. of vertical deflection can be obtained without overloading. The unit has a regulated power supply; sweep is continuously variable to 150 kc. *El-Tronics, Inc., 5th & Noble Sts., Philadelphia, Pa.* (P-35)

Regulated Power Supply

The model RE-2002, designed for general laboratory use, provides a stable, regulated, adjustable source of high d-c voltage with low ripple. This supply uses a balanced, two-stage, high-gain feedback amplifier as a regulator with a stability ratio of 10^6, an internal impedance under 0.5 ohm at d-c, and a ripple under 0.5 mv, peak to peak. The output voltage is adjustable to ±2% over the range 700–2,020 volts; current rating is 0–25 ma. *Northeast Scientific Co., 1 Gray St., Cambridge 38, Mass.* (P-36)



Pneumatic Control

The Metagraphic System, a three-part pneumatically-operated instrument combination comprised of transmitter, receiver (recorder or indicator) and controller, indicates, records and controls pressure, vacuum, temperature, liquid level, differential pressure and flow. A universal 3–15 lb/in.² air-pressure signal interconnects the three units no matter what variable is being transmitted. Strip-chart recorders and indicators are interchangeable without loss of signal or control. *The Bristol Co., Waterbury 20, Conn.* (P-37)

Electric Stopwatch

The Time-It stopwatch, which utilizes the accuracy of its electric power source, is offered in two models, one of which registers up to 1,000 min in 0.01-min intervals, and the other up to 10,000 sec in 0.1-sec intervals. Both models have a clear indicating counter with large, legible numbers. Reset knob is located on the left side to free the right hand for writing. *Precision Scientific Co., 3737 W. Cortland St., Chicago 47, Ill.* (P-38)

Ballistic Meter

The S-43X 5-in. ballistic meter uses a large movement (the same size as large switchboard meters) to achieve the extremely sluggish action desired for ballistic-type meters. These instruments can be furnished in any type and range; most sensitive recommended range is 0–200 μa which has 2,500-ohm resistance. These instruments are available with or without illumination. Dials are hand drawn for each order. *Hickok Electrical Instrument Co., 10588 Dupont Ave., Cleveland 8, Ohio.* (P-39)

Subminiature Resistors

The Glennite subminiature resistors are made of a special material deposited on a thin ceramic base. By varying the composition of the material, a wide range of resistance values is covered with little change in physical size. These resistors are available from 50 ohms to 1 megohm, and are selected for specified tolerances. Normal rating is 0.1 watt; 0.25-watt resistors are available on request. *Glenco Corp., Metuchen, N. J.* (P-40)

High-Vacuum System

This high-vacuum system was designed for electron microscopes and can pump down a 12-in. bell jar in 3 min. It has a pumping speed of 260 liters/sec with the diffusion pump and 5 ft³/min with the mechanical pump, and is said to produce pressures of 10^{-5} or lower. *High Vacuum Equipment Corp., Bingham, Mass.* (P-41)

Power Supply

The type 3-132 power supply is designed for excitation of multiple-strain gages and other resistance-type transducers and as a convenient supply for sensitive filaments in d-c amplifiers, recording lamps and standard light

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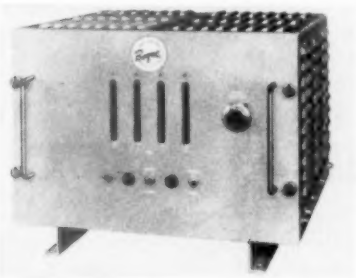
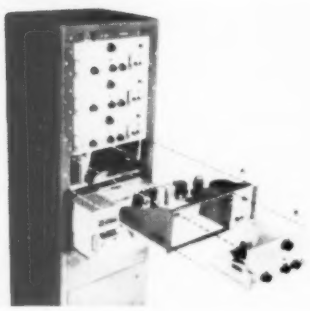
sources. The supply is continuously adjustable over its 0–15 volt d-c range and delivers a maximum of 1 ampere. Output impedance is less than 0.1 ohm, drift less than 5 mv/hr and ripple less than 1 mv peak-to-peak. *Consolidated Engineering Corp., 300 N. Sierra Madre Villa, Pasadena 8, Calif.* (P-42)



Liquid-Level Indicator

The model SL-102 sonic liquid-level indicating system indicates liquid levels within ±0.01 ft. The system uses an ultrasonic pulse ranging technique. It is also suited to applications requiring the location of the demarcation line between immiscible liquids. A direct level reading in tens, units, tenths and hundredths of a foot is presented on illuminated decimal counters. One common indicator can gage any number of transducer-equipped tanks within a radius of 2,000 ft. *Bogue Electric Mfg. Co., 52 Iowa Ave., Patterson 3, N. J.* (P-43)



Oscillographic Recorder

The model 150 oscillographic recording system provides a combination of interchangeable plug-in elements for the graphic registration of phenomena (individually or up to four simultaneously) within the range of zero to 100 cycles/sec. The system consists of a four-channel recorder assembly and a driver-amplifier and power supply (A in illustration) for each of the four channels. The preampli-

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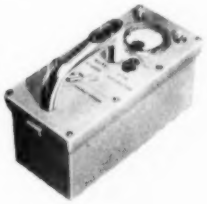
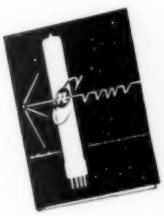
New Model 2582 — "Samson" portable ionization chamber instrument for area measurement of *low level* alpha, beta or gamma contamination.



New Model 2715 — "Nemo" portable neutron survey meter. Measures fast and thermal neutrons separately on special logarithmic meter.



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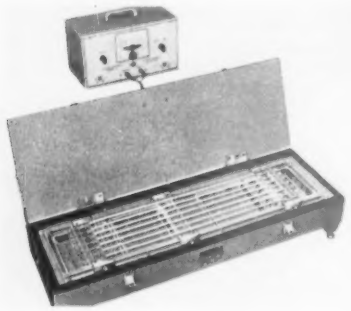
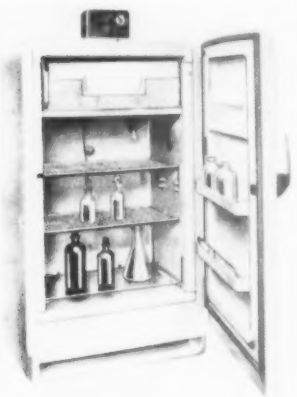
fier (B), required for the specific application, is plugged into the appropriate channel. The unit has stylus temperature control for each channel; control of input signals is attained by ratios of 1, 2 and 5 on an attenuator. A selection of nine paper speeds is provided on one control. The recorder slides out for inspection or for notations. *Sanborn Co., Cambridge, Mass.* (P-44)



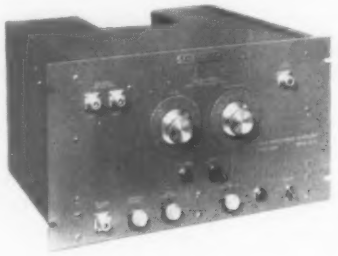
Ionograph

The Junior Ionograph separates and identifies mixtures of biological materials, such as amino acids and proteins. It accommodates 7 filter paper strips or a single sheet for 2-dimensional electromigrations. Potential range is 150–500 volts, regulated. The Junior Ionograph is a modified Precision Ionograph and, while not as versatile, is a less expensive instrument. *Precision Scientific Co., 3737 W. Cortland St., Chicago 47, Ill.* (P-45)



Incubator

This B.O.D. incubator is designed to afford closer temperature control and greater uniformity during low-temperature incubations. It has a range of 5–50° C, an accuracy of ±0.5° C, and forced circulation. Working space is $8\frac{1}{2}$ ft³. The incubator employs a hydraulic thermostat and a heating coil to stabilize the cooling cycle when operating near room temperature. *Precision Scientific Co., 3737 W. Cortland St., Chicago 47, Ill.* (P-46)



Sweep Generator

The model 610 sweep generator is designed to supply extremely fast sweeps for cathode-ray indicators or other applications requiring a rapidly rising linear voltage. Sweep speeds are continuously adjustable from 0.05 to 500 cm/μsec and can be triggered for single or repetitive sweeps. The generator also provides a brightening pulse and gate outputs. When used with the SKL model 600 cathode-ray indicator, maximum sweep speed is 200 in./μsec. *Spencer-Kennedy Laboratories, Inc., 186 Massachusetts Ave., Cambridge 39, Mass.* (P-47)

INDUSTRY NOTES

▶**General Electric Co. Ltd.,** London, England, filled a $1,400,000 order by the British Ministry of Supply for furnaces and furnace pots for use in the production of purified uranium metal. The 54 electric vertical cylinder furnaces, each rated at 100 kw, and 200 furnace pots are in use at the Springfields factory of the Atomic Energy Authority.

▶**El-Tronics, Inc.,** Fifth and Noble Sts., Philadelphia 23, Pa., shipped 1,200 Rad-Tek radiation survey meters in April to the Federal Civil Defense Administration.

▶**Tracerlab, Inc.,** 130 High St., Boston 10, Mass., has had atomic batteries under development for the past year and a half. Developed by Alexander Thomas under a Signal Corps contract, battery utilizes tritium surrounding bimetallic electrodes. Up to 400 volts at 0.01–1.0 watts can be provided. Optimum useful life is 18 yr. Tracerlab has appointed Homer S. Myers as industrial-products manager. Mr. Myers was formerly president of Radioactive Products, Inc., and one of the original founders of Tracerlab.

▶**Corning Glass Works,** Corning, N. Y., successfully cast and assembled glass windows claimed to be the heaviest in the world, for the AEC engine test facility at the National Reactor Testing Station, Idaho. Corning is furnishing the windows under a contract that Utah Construction Co. has for the initial portion of the aircraft nuclear propulsion facility.

LITERATURE AVAILABLE

Handling equipment. Folder 75 gives information on platform, tray, rack, and universal trucks for handling production and test equipment. *Wilder Mfg. Co., Inc., Mechanic St. and Erie R.R., Port Jervis, N. Y.* (L-1)

Printed circuits. Bulletin describes sockets designed for printed circuit operation. *Mycalex Corp. of America, Clifton Blvd., Clifton, N. J.* (L-2)

Precision resistors. Bulletin gives specifications of encapsulated wirewound resistors. *Shallcross Mfg. Co., Collingdale, Pa.* (L-3)

Refractories. Pamphlet gives research suggestions for refractory users and producers, and includes mean thermal conductivity conversion chart. *Battelle Memorial Institute, 505 King Ave., Columbus 1, Ohio.* (L-4)

Solenoid valves. Bulletin 55 covers line of ¾-in. solenoid-controlled, pilot-operated, 4-way valves. *Pantex Mfg. Corp., Pawtucket, R. I.* (L-5)

Volt-ammeter. Brochure describes transfer volt-ammeter accurate within 0.05% through a range of 20–20,000 cps. *Charles Englehard, Inc., 850 Passaic Ave., E. Newark, N. J.* (L-6)

Microwave transmission. "Coaxial Transmission Lines and Waveguide" booklet discusses and illustrates transmission lines, microwave cable adapters, hangers for transmission lines, dehydration and accessories, antennas, etc. *Prodelin, Inc., 307 Bergen Ave., Kearny, N. J.* (L-7)

Viscometer. "Solutions to Sticky Problems" gives information on use and care of Brookfield viscometer. *Brookfield Engineering Laboratories, Inc., Stoughton, Mass.* (L-8)

Voltage regulator. Bulletin 01B6056D describes transformer-type

$\frac{5}{8}$% feeder voltage regulators. *Allis-Chalmers Mfg. Co., 1316 S. 70th St., Milwaukee, Wis.* (L-9)

High-resistance measurement. Engineering note describes two accurate methods of measuring high resistances. *Keithley Instruments, 3868 Carnegie Ave., Cleveland 15, Ohio.* (L-10)

Industrial devices. Folder discusses measuring, indicating, recording and controlling devices for use in many industries. *Schaevitz Engineering, Box 505, Camden 1, N. J.* (L-11)

Connectors. Bulletin gives information on series E-Z 16 connectors with coaxial contacts. *DeJur-Amsco Corp., Electronic Sales Div., 45-01 Northern Blvd., Long Island City, N. Y.* (L-12)

Pumps and flow regulators. Catalogs 10-F-70 and 91-106 describe self-operating flow regulator and automatic pump sequence control system. *Fischer & Porter Co., 49 Jacksonville Rd., Hatboro, Pa.* (L-13)

Magnetic amplifiers. Bulletin S235-1-54 lists line of 60- and 400-cps magnetic servo amplifiers and magnetic amplifier servo systems and their servo performance. *Magnetic Amplifiers, Inc., 632 Tinton Ave., New York 55, N. Y.* (L-14)

Radiation detection. Description of sensitive, economical, miniature Geiger counters given in brochure. *Micro Specialties Co., 1834 University Ave., Berkeley 3, Calif.* (L-15)

Thermostats. A thermostatic slide-rule computer is available without charge if requested on letterhead. *Mechanical Industries Production Co., 217 Ash St., Akron 2, Ohio.* (L-16)

Thermometers. Bulletin 2247 describes strain-free platinum resistance thermometers. *American Instrument Co., Inc., Silver Spring, Md.* (L-17)

Valves. Data Unit 234 gives applications and specifications of valves for instrument piping and general use. *Jerguson Gage & Valve Co., 80 Fellsway, Somerville 45, Mass.* (L-18)

Educational equipment. Catalog EC-2 contains information on combination science desks, center tables and instructors' desks for school laboratory. *Metalab Equipment Corp., 214 Duffy Ave., Hicksville, N. Y.* (L-19)

Angle and phase meters. Laboratory Report 9 features applications of experiments with types 310-A Z-angle

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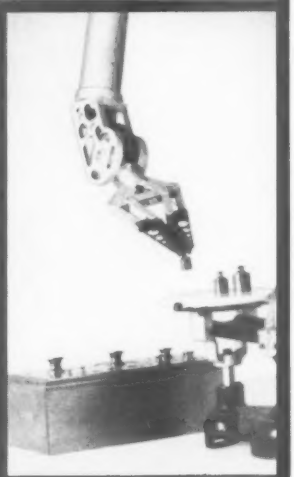

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meter and 320-AB phase meter in school laboratories. *Technology Instrument Corp., 531 Main St., Acton, Mass.* (L-20)

Gas analyzers. Analyzer for detection of toxic gases and instrument that can analyze hydrogen and hydrocarbons are discussed in brochures. *Teller & Cooper, Inc., 75 Front St., Brooklyn 1, N. Y.* (L-21)

Electrophoresis. Bulletin 690 describes equipment for electrophoretic separations on wet filter paper. *Precision Scientific Co., 3737 W. Cortland St., Chicago 47, Ill.* (L-22)

Power supplies. Catalog 254 includes line of a-c voltage regulators, regulated d-c sources and B supplies, frequency changers, inverters, magnetic amplifier d-c sources and related equipment. *Sorensen & Co., Inc., 375 Fairfield Ave., Stamford, Conn.* (L-23)

Temperature control. Bulletin 120 describes the operation of the Aero Heat Exchanger used in controlling temperatures of industrial liquids. *Niagara Blower Co., 405 Lexington Ave., New York 17, N. Y.* (L-24)

Water demineralizing. Catalog 127 describes line of mixed-bed, two-bed and four-bed demineralizers for laboratory, hospital and industrial use. *Barnstead Still & Sterilizer Co., 222 Lanesville Terrace, Forest Hills, Boston 31, Mass.* (L-25)

Computers. Volume 5, No. 1-2 of the Hewlett-Packard Journal gives techniques for making time-interval measurements involving high-speed clutch systems, relay operating times, and phase delay at very low frequencies. *Hewlett-Packard Co., 395 Page Mill Rd., Palo Alto, Calif.* (L-26)

Chemical pumps. Catalog Section 100 deals with designs of regenerative turbine pumps for chemical service and gives evaluation of mechanical seals available in turbine pumps. *Roy E. Roth Co., 2420 4th Ave., Rock Island, Ill.* (L-27)

Services and products. Catalog describes design-development-production-assembly work and ability to miniaturize assemblies and to redesign products. *Allied International Inc., Allied Engineering Div., Conn. and Richards Avenues, S. Norwalk, Conn.* (L-28)

Radiation detection. "The Nucleus" gives data on detecting soft beta radiation, health safety in radioisotope

laboratory, scintillation counters and their medical applications, and economical Co^{60} source shielding. *Nuclear Instrument & Chemical Corp., 229 W. Erie St., Chicago 10, Ill.* (L-29)

Water filter. Bulletin WC-115 gives data on diatomite filters for purifying water supplies. *Graver Water Conditioning Co., 216 W. 14th St., New York 11, N. Y.* (L-30)

Laboratory Equipment. Catalog 20 displays variety of equipment for laboratory. *Scientific Glass Apparatus Co., Inc., Bloomfield, N. J.* (L-31)

Laboratory equipment. "Laboratory specials" describes line of scientific laboratory equipment. *Aloe Scientific Div., A. S. Aloe Co., 5655 Kingsbury Ave., St. Louis 12, Mo.* (L-32)

Centrifugal pump. Dynapump brochure describes fractional-hp pump driven by rotating magnetic field. *The Fostoria Pressed Steel Corp., Fostoria, Ohio.* (L-33)

Radiation detection. Bulletins 473, 501, 492, and 485 give characteristics of a G-M classroom demonstration set, beta/gamma survey instrument, binary scaler counter set and decade scaler counter set, respectively. *El-Tronics, Inc., 2647 N. Howard St., Philadelphia 33, Pa.* (L-34)

Valves. Publication 5200 gives relief valve data for steam, air and gas service and suggests how to select proper valve. *Cochrane Corp., 17th St. & Allegheny Ave., Phila. 32, Pa.* (L-35)

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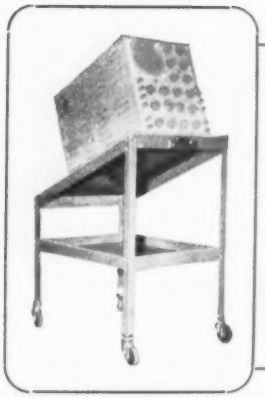

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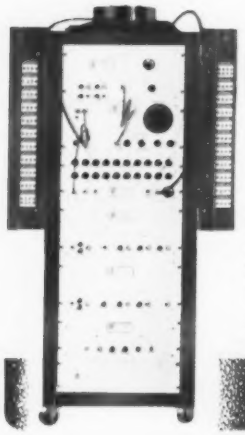

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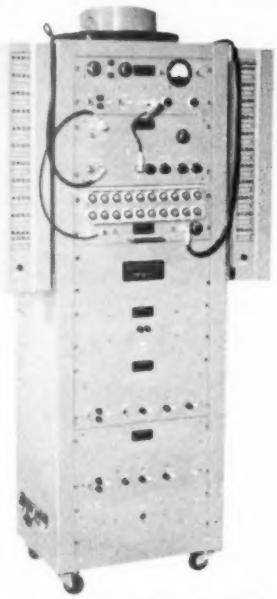

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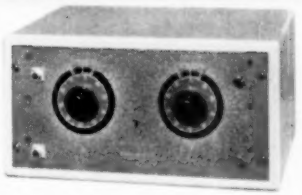

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